T.R.
TURKISH NAVAL ACADEMY
NAVAL SCIENCE AND ENGINEERING INSTITUTE
DEPARTMENT OF OPERATIONS RESEARCH

A MULTI-METHODOLOGICAL APPROACH FOR ROADWAY LIGHTING SELECTION

A Master Thesis

SEMİH BARBAROS ÜSTÜN

Advisor: Asst. Prof. İlker AKGÜN

İstanbul, 2015

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DEDICATION

Tüm aileme, sevdiklerime ve ülkeme

DISCLAIMER STATEMENT

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Turkish Naval Forces, Turkish Naval Academy and Naval Science and Engineering Institute. I declare that all materials in this thesis are used according to academic rules and ethics. All accommodated out-sources are included in the references section and these out-sources are referred inside the thesis where they are included.

ÖZET

DIŞ AYDINLATMA SEÇİMİ İÇİN ÇOK KRİTERLİ KARAR VERME YAKLAŞIMI

Semih Barbaros ÜSTÜN

Harekat Analizi Yüksek Lisans Tezi, 2015

Danışman: Yrd.Doç.Dr. İlker AKGÜN

Anahtar Kelimeler: Basit Ağırlıklı Toplama, Çok Kriterli Karar Verme, Kalite Fonksiyon Yayılımı, LED, Veri Zarflama Analizi, Enerji Verimliliği, Yol Aydınlatması

Yol aydınlatma seviyesi gece koşullarında karayolu ve sürüş güvenliği için önemli bir faktör olmakla beraber, ekonomik ölçütler nedeniyle karayolu aydınlatma maliyeti de önemlidir. Bu maliyet, hükümet ve yerel belediyelerin sorumluluğundadır. Bu nedenle bu kurumların bütçelerine tasarruf sağlamak amacıyla bu maliyeti yönetmeleri ihtiyacı doğar ve bu tasarrufu gerçekleştirebilmeleri için verimli enerji projelerine odaklanmaları gerekmektedir. Bunun en yaygın yolu, mevcut aydınlatmaları ekonomik ömürlerinin bitiminde ya

da öncesinde verimlileriyle değiştirmektir. Eski sistemler enerji maliyetlerini arttırır bunun yanında günümüz teknolojisi, karayolu aydınlatma tesisatlarının değiştirilmesi durumunda büyük bir maliyet tasarrufu potansiyeli sunar.

Ekonomik ve teknik açıdan ömrünü doldurmuş eski sokak ve yol aydınlatmalarını değiştirmek için en verimli yol aydınlatması alternatif seçimi yolların idari sorumluları olan yerel hükümetler, belediyeler ve üniversiteler açısından çok karmaşık stratejik bir sorun olmuştur. Çünkü maliyet ve enerji verimliliği, dizayn gereksinimleri, idari beklentiler ve çevresel unsurlar gibi hem kalitatif hem de kantitatif olan iç ve dış değerlendirmeleri gerektirmektedir.

Bu tezin amacı, verimli yol aydınlatması seçim problemini çok kriterli karar verme yöntemlerinden özgün bir biçimde yapılandırılmış Veri Zarflama Analizi (VZA), Kalite Fonksiyon Yayılımı (KFY) ve Basit Ağırlıklı Toplama (BAT) yöntemlerini birlikte kullanmaya dayalı çok yöntemli sistematik bir yaklaşımla analiz etmektir. Çok metodlu yönteme dayanan bu yaklaşımın özelliği maliyet ve enerji tüketimini azaltmasının yanında, yol aydınlatması enerji verimliliğini arttırması ve geliştirmesi önemli bir avantajdır.

Örnek olay çalışması olarak bir üniversite kampüsü için yol aydınlatması seçimi incelenmiş, maliyet, enerji tüketimi ve müşteri isterleri açısından en verimli ve uygun yol aydınlatması alternatif seçimi analiz edilmiştir. Sonuçlar göstermiştir ki özgün bir biçimde oluşturulmuş çok kriterli karar verme yöntememiz efektif ve verimli yol aydınlatması seçimi için büyük avantajlar sağlamaktadır. Bu özgün çok kriterli karar verme yaklaşımı ayrıca oldukça basit ve iyi yapılandırılmış bir karar verme aracı olarak bu tür stratejik karar verme problemlerine uygulanabilir.

ABSTRACT

A MULTI-METHODOLOGICAL APPROACH FOR ROADWAY LIGHTING SELECTION

Semih Barbaros ÜSTÜN

Operations Research, Master of Science Thesis, 2015

Advisor: Asst.Prof. İlker AKGÜN

Key Words: Data Envelopment Analysis (DEA), Energy Efficiency, LED, Multiple Criteria Decision Making (MCDM), Roadway Lighting, Simple Additive Weighting (SAW); Quality Function Deployment (QFD)

Selecting the most efficient roadway lighting alternative to change or to replace the old streetlights has become a highly complex strategic activity for local governments, municipalities, universities as road keepers and it necessitates consideration of both internal and external factors which can be both qualitative and quantitative as cost efficiency, energy efficiency, design requirements, administrative expectations and environmental factors.

The objective of this thesis is to propose an originally structured multi-methodological approach based on the systematic application of Data Envelopment

Analysis (DEA), Quality Function Deployment (QFD) and Simple Additive Weighting (SAW) methods to support critical decision process on roadway lighting selection under multiple criteria decision making (MCDM). Apart from its accuracy, this method, which is based on a multi-methodological approach, has the added advantage of enhancing the energy efficiency of roadway lighting.

As a case study, roadway lighting alternatives for a university campus are analyzed to select the most suitable of them for the energy and cost efficiency that is evidently a priority for the world today. The results show that the proposed multi-methodological approach takes the advantages of DEA, QFD and SAW to select an efficient roadway lighting alternative. The DEA is exercised to distinguish the efficient alternatives; the QFD is used to learn and find out customer requirements and satisfy these requirements. Lastly, the SAW is utilized to rank the alternatives which are distinguished efficient by DEA method. Proposed approach also provides a relatively simple and very well suited decision-making tool for this type of strategic decision making problems.

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ABBREVIATIONS

CEN : European Committee for Standardization

CIE : International Commission on Illumination

CRS : Constant Returns to Scale

DEA : Data Envelopment Analysis

DMU : Decision Making Unit

HoQ : House of Quality

HPS : High Pressure Sodium

HPM : High Pressure Mercury

LED : Lighting Emitting Diode

LRC : Lighting Research Center

MCDM : Multi Criteria Decision Making

MH : Metal Halide

QFD : Quality Function Deployment

SAW : Simple Additive Weighting

SR : Surround Ratio

TEDAS : Turkish Electricity Distribution Company

TI : Threshold Increment

VOC : Voice of Customers

VRS : Variable Returns to Scale

1 INTRODUCTION

1.1 Overview

Selecting the most efficient roadway lighting alternative to change or to replace the old streetlights has become a highly complex strategic activity for local governments, municipalities, universities as road keepers and it necessitates consideration of both internal and external factors which can be both qualitative and quantitative as cost efficiency, energy efficiency, design requirements, administrative expectations and environmental factors. Technical information is expressed in this section to ensure the motivation on road lighting selection process.

Roadway lighting alternative selection is one of the complex business disciplines that include a great number of decision-making processes and strategic cases which are executed by road keepers within several divisions of the governmental organizations in global market environment of energy industry.

Municipalities, university administrators and governments are under pressure to meet energy conservation goals by reducing their energy consumption while complying with lighting norms and standards. Outdated installations increase energy costs and new technology represents a large cost cutting potential in the rehabilitation of outdoor lighting installations.

With new roadway lighting installations there is great saving potential when employing new enriching adaptive lighting techniques which are possible with today's high technology. (Kostic et al., 2009)

The other saving and energy conservation method is selecting a combine of roadway lighting alternative to produce high quality lighting by means of marketing support and electricity savings with minimal ecological impact. (Das et al., 2015)

In general, the energy and cost efficiency of the governments or municipalities are depends on availability of well-structured road lighting systems, effective management style, integration of technology and innovation into business cycle to manage the cost and energy efficiency and safer driving conditions.

The complex configuration of road lighting creates pressure the critical decision-making processes. Therefore, the road keepers as decision-makers in this segment of energy industry require analytical tools and quantitative methodologies to manage the administrative, marketing, technical, environmental and functional decision processes in an effective manner.

In recent years energy saving policies applied in road lighting entirely the world have started replacement of old luminaires by efficient new luminaries. There are four lamp technologies; High Pressure Sodium (HPS) lamps, High Pressure Mercury (HPM) lamps, Metal Halide (MH) lamps and Light Emitting Diodes (LED). The street outdoor lighting takes a share of 4.73% of the overall tertiary sector electricity consumption according to Energy Efficiency Status Report of European Commission (2012). The percentage of general lighting, which road lighting is weighted in it, is 2% in Turkey according to The Annual Energy Report of Turkey Energy Distribution Company.(TEDAS, 2013)

As a consequence, the market for replacement or renovation of roadway lighting installations is sufficiently large to attract road keepers' attention to optimize the cost and energy.

At this point, a MCDM situation on selection of efficient road lighting among the installation alternatives is faced by municipalities, governments, university administrators and managers in energy market. This study proposes an originally structured approach by using DEA, QFD and SAW methods to economically evaluate the relative efficiency in economic viewpoint of energy industry and customer requirements which are the needs of whom use the roads.

1.2 Objectives

The main objective of this thesis is to propose an originally structured multi-methodological approach based on the systematic application of DEA, QFD and SAW methods to support critical decision process on roadway lighting selection under multiple criteria decision making (MCDM). Apart from its accuracy, this method, which is based on a multi-methodological approach, has the added advantage of enhancing the energy efficiency of roadway lighting.

As a case study, roadway lighting alternatives are analyzed to select the most suitable of them for the energy and cost efficiency that is evidently a priority for the world today. The results show that the proposed multi-methodological approach takes the advantages of DEA, QFD and SAW to select the most efficient roadway lighting alternative. Proposed approach also provides a relatively simple and very well suited decision-making tool for this type of strategic decision making problems.

First of all, before the steps of this proposed approach there is need to explain standards and specifications of roadway lighting. The roadway lighting standards and specifications are defined by international/national lighting publications such as lighting classes. The lighting classes are constituted for preventing the excessive energy consumption and sufficient lighting for every road. The lighting classes are determined by a set of photometric necessities purposing at the visual requirements of certain road users in certain types of road areas and environment. (CEN/TR 13201-2)

Also lighting classes identified in International Commission on Illumination publication CIE 115: 2010. However there are several lighting classes, the ME classes in EN13201 and M classes in CIE 115:2010 is the concern of this paper. Because the ME classes are contained for drivers of motorized vehicles for user on traffic routes, and in some countries also residential roads, allowing medium to high driving speeds [EN 13201-2] and are shown Table 1-1 [CIE 115:2010]. This thesis analyzes the double-side luminaire arrangements and a selected lighting classes for roadway based on the CIE standards. In despite of analyzed one type of roadway lighting classes, this proposed approach is generic method and can be studied and implemented for every type of roadways.

Table 1-1 The Roadway Lighting Standards

Class	Luminance of the road surface of the carriageway for the dry road surface condition			Disability glare	Lighting of surroundings
	L_0 in cd/m2	U_0	U_1	TI in %	SR
M1	≥2.0	≥0.40	≥0.70	≤10	≥0.5
M2	≥1.5	≥0.40	≥0.70	≤10	≥0.5
M3	≥1.0	≥0.40	≥0.60	≤10	≥0.5
M4	≥0.75	≥0.40	≥0.60	≤15	≥0.5
M5	≥0.50	≥0.35	≥0.40	≤15	≥0.5
M6	≥0.30	≥0.35	≥0.40	≤20	≥0.5

L_0:average road surface luminance; **U_0**: average uniformity; **U_1**: longitudinal uniformity; **TI**: threshold increment; **SR**: surround ratio

1.3 Structure

This thesis has six chapters. Chapter One is an introductory chapter including an overview of the thesis, objectives, and structure.

In Chapter Two, literature review of the existing approaches and the factors that influence the roadway lighting selection.

Chapter Three consists the theoretical frameworks of DEA, QFD and SAW which are represented introductory and explanatory part for the proposed approach.

In Chapter Four, the proposed approach and the process flow of this approach are introduced and explained.

Chapter Five includes an illustrative case study of proposed approach for roadway lighting selection.

Chapter Six includes the conclusions of the thesis and further remarks.

2 LITERATURE REVIEW

2.1 Background and Definitions

First of all there is a need to define purpose of roadway lighting; is to reach a level of visibility which enables the driver and pedestrian to see quickly, clearly, and with certainty all significant detail, obviously the alignment of the road and any obstacles on the roadway.

After the purpose of roadway lighting general lighting terms that used this study are defined.

- *The light* is visually evaluated radiant energy.
- *Visibility* is the quality or state of being perceivable by the eye.
- *Lumen* is the amount of light energy generated by a light source. Lights are typically rated for their efficiency in lumens per watt, where watts are a measure of the amount of electricity a fixture uses.
- *Luminaire* is a complete unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps and to connect the lamps to the power supply.
- *Luminous intensity* is the force of luminous flux in a specified direction, measured in candela (cd).
- *Luminous flux* is time rate flow of light, measured in lumen (lm). One lumen is the amount of light which falls on an area of one square foot.
- *Luminous existance* is total amount of luminous flux reflected or transmitted by a source, measured in lm/m^2.

- *Illuminance* is the density of luminous flux incident on a surface, measured in footcandles, fc (lux, lx). One footcandle is the illumination of a surface one square foot in area on which there is a uniformly distributed luminous flux of one lumen.
- *Luminance* (photometric brightness) is the quantity of luminous flux emitted, reflected, or transmitted from a surface in a particular direction, measured in cd/ft^2 or cd/m^2. This is the property of light we can visibly see with our eyes.

2.2 Data Literature Survey on Roadway Lighting

Despite the ongoing discussions on the roadway lighting, researches, studies and analyses using the analytical methodologies have been so rarely seemed in the literature. Mostly safety issues and technical analysis of roadway lighting and economic analysis have been worked through but there is a need to analyze by terms of MCDM for an analytical, economical, customer, budget and environment friendly, technically efficient analysis of roadway lighting alternative selection.

As an example of technical study by Mayeur et al (2010); the target detection performances are examined by comparing driver and pedestrian status conditions. Balancing for depreciation and decreasing the number of installations or the amount of over sizing of lamp power are very significant for urban lighting selection as reported by Coureaux and Manzano (2013).

According to Kostic et al. (2013), a complete techno-economic analysis which compared financially road lighting solutions realized by MH and HPS lamps is inspired by the results of previous theoretical and experimental research in the field of mesopic vision. To improve a more systematic approach, Mirzaei et al. (2013)

proposed an asset management model for offering optimal performance strategies and discussing challenges facing regulators, managers, and operators of public-lighting systems. However, management of public lighting is concentrated by this study; it does not contain the main tendencies as energy efficiency or lighting standards on this issue.

Rabaza et al. (2013) also presented a new methodology for calculating roadway lighting design based on a multi-objective evolutionary algorithm which optimizes uniformity and installation efficiency in public lighting.

On the other hand, comparative evaluation of the lighting technologies and applications testing on field by Lighting Research Center (LRC) is another overall approach in the literature. (2015) LRC field test is based on comparing of LED technology by weighing benefits relative to conventional light sources on performance indicators.

In addition Wu et al. (2010) presented the energy conservation analysis of roadway lighting for economic feasibility by using HPS, mercury and solar powered LED. Recently, Liu (2014) compared economic sufficiency of islanded and grid-connected system for the street lighting systems.

Also Kostic, Djokic (2015) offered important recommendations about the related influencing factors for energy savings in road lighting. Recently, Radulovic et al. (2011) have proposed an analysis to designate the connection of energy market liberalization and sustainable improvement in cities on the public lighting energy management in the Croatian city of Rijeka. Yi Jiang et al (2015) conducted a new analysis to contrast the new technologies with the conventional HPS which are commonly in use in Indiana. Table 2-1 summarizes these existing approaches that have been proposed to support roadway lighting selection process.

Table 2-1 The approaches on roadway lighting

Proposed Approach	Description	Author(s)	Year
IBM-MPS X(an integer programming algorithm)	A measurable forecasting of the utility accruing from street lighting in Jerusalem	Shefer & Stroumsa	1982
The cost discount method	A complete techno-economic analysis to compare financially road lighting solutions realized by MH and HPS	Kostic et al.	2009
Qualitative method	Recommendations which result from user requirements with regard to visual quality	Kostic & Djokic	2009
Economic analysis	An energy conservation analysis of roadway lighting for economic feasibility by using HPS, mercury and solar powered LED	Wu et. al.	2009
$Omega^2$	A study of the target detection performances by comparing driver and pedestrian status conditions	Mayeur, Bremond & Bastien	2010
A mathematical model of the public lighting electric grid	An analysis to designate the connection of energy market liberalization and sustainable improvement in cities on the public lighting energy management in the Croatian city of Rijeka	Radulovic et. al.	2011
Luminaire depreciation	A study of balancing for depreciation and decreasing the number of installations for urban lighting selection.	Coureaux & Manzano	2013
Multi-objective evolutionary algorithm	A methodology for calculating roadway lighting design based on a multi-objective evolutionary algorithm which optimizes uniformity and installation efficiency.	Rabaza et. al.	2013
Computer-based renewable energy simulation tool	A compared economic sufficiency of islanded and grid-connected system for the street lighting systems.	Lui	2014
Optimal asset management strategy	An asset management model for offering optimal performance strategies of public lighting systems.	Mirzaei et. al.	2015
Cost Effectiveness	A cost effectiveness analysis to contrast the new technologies with the conventional HPS in India	Jiang, Li, Guan & Zhao	2015

Although there are some previous studies describing the roadway lighting selection factors as Shefer, Stroumsa (1982) whom presented an earlier process for the inclusive measurable forecast of the utility accruing from street lighting, these studies are not appropriately utilized for ensuring the real case expectations and they are not both technical and customer focused analytical approaches at the same time. Therefore, structuring an analytical and effective evaluation model on roadway lighting selection process is necessary to identify the authorities' decision factors consistently.

3 THEORETICAL BACKGROUND

3.1 Introduction

The DEA, QFD and SAW methods are applied to select energy and cost efficient roadway lighting alternative considering customer requirements and expectations in this thesis as a unique multi- methodological approach. Before the introducing this multi-methodological approach, there is a need to express the methods. The fundamentals, the bases and the theoretical framework of the proposed DEA, QFD and SAW methods are presented in the further sections respectively.

3.2 Brief overview on DEA methodology

DEA methodology was firstly introduced by Charnes, Cooper and Rhodes in 1978 and is a non-parametric method used to measure the relative efficiency of decision making units (DMUs). A DMU is an entity which performs the same function by transforming multiple inputs into multiple outputs, through using a number of inputs to produce outputs. The efficiency of a certain DMU is measured by $\frac{output}{input}$ (Cooper et al, 2000).

Processes can be considered as a black box and the relationships between inputs and outputs can be analyzed by DEA. DEA runs all the data available to analysis the best practice empirical frontier. The advantage of DEA is that its characteristic to evaluate relative efficiencies of DMUs without prior weights on the underlying functional relationships between inputs and outputs. As a consequence, each unit is sorted in the best possible option in proportion to the other units in this analysis.

The DEA models are mainly categorized as radial and non-radial DEA models. The radial DEA models contain the Charnes, Cooper and Rhodes (CCR) ratio model (the radial form under constant returns to scale, where returns to scale stands for returns to scale) and the Banker, Charnes and Cooper (BCC) model (the radial form under variable returns to scale). An independent approach between output orientation and input orientation is necessary for the radial type of efficiency measurement (Azadi et al., 2013). The non-radial models are not used in this thesis.

The CCR model computes the efficiency of each DMU once with given data and therefore there is a need for n optimizations, one for each DMU to be analyzed. Assume the DMU_j is the analyzed on any test be nominated as DMU_o where o arranges in order 1,2,…, n. The input weights are indicated as v_i and the output weights are indicated as u_r where i = 1, 2, …, m and r = 1, 2, …, s. The basic CCR model is shown as follows (Cooper et al, 2000) :

$$\max E_o = \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}}$$

subject to

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1 \quad j = 1, 2, ..., n$$

$$v_i, u_r \geq 0 \tag{1}$$

Below the envelopment form and the multiplier form of the CCR DEA problem are presented, with input orientation and assuming Constant Returns to Scale (CRS) or for DMU_0 (Cooper et al., 1982) :

Table 3-1 CRS DEA model

Envelopment Form	**Multiplier Form**
$Min_{\theta,\lambda}\ \lambda$	$Max_{u,v}\ uy_{0,}$
subject to:	subject to:
$-y_0 + Y\lambda \geq 0$	$uY - vX \leq 0$
$\theta x_0 - X\lambda \geq 0$	$vx_0 = 1$

This model has to be run individually for each of the *n* DMUs compared to identify the relative efficiency. In the primal and dual models presented, u and v are row vectors of input and output weights, x_0 and y_0 column vectors of the inputs used and the outputs produced by DMU_0 under evaluation, *X* and *Y* are input and output matrices representing the data for all *n* DMUs, θ is a scalar representing the radial reduction in all inputs used by DMU_0 and λ is a column vector of intensity variables, reflecting the weight to be attached to each DMU in forming the efficient benchmark for the DMU_0 under analysis. θ is the radial efficiency measure for DMU_0, and will be equal to 1 if the DMU is radially efficient, and smaller than 1 if the DMU is inefficient when compared with the other DMUs (Amado et al., 2013).

The DEA input oriented radial model is Variable Returns to Scale (VRS or BCC) with only difference to the CRS version inclusion of the convexity restriction of $\sum_{j=1}^{n} \lambda_j = 1$ in the envelopment form. (Banker et al., 1996)

When literature is reviewed, the method is evaluated in the various application fields as follows; Energy: (Cui et al., 2015), (Han et al., 2015), (Cui et al., 2014), (Chauhan et al., 2006); Banking: (Tsolas et al., 2014), (Wanke et al., 2014), (Liu et al., 2015), (Lim et al., 2014); Transportation: (Cui et al., 2014), (Bray et al., 2015); Finance: (Halkos et al., 2012); Agriculture: (Ederer, 2015), (Chauhan et al., 2006); Manufacturing: (Yu et al., 2014); Health: (Mitropoulos et al., 2014); Government: (Fuentes et al., 2015); Chemical industry: (Han et al., 2015); Aviation: (Cui et al., 2015).

If our performance measurement is minimizing the inputs and maximizing the outputs then the DEA problem becomes a common benchmarking problem which DEA is employed as a MCDM tool. (Cooper et al., 2000)

DEA can be applied as a MCDM tool in all areas for generic benchmarking and as can be seen above DEA is a MCDM tool to benchmark the alternatives for roadway lighting.

3.3 The Fundamentals of QFD

The QFD is used to understand the customer requirements and satisfy these requirements in order to select the most efficient roadway lighting alternative by customer-driven respond in this thesis. QFD was introduced as a concept by Japanese in 1967. QFD is “an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production (i.e., marketing strategies, planning, product design and engineering, prototype evaluation, production process development, production, sales)" (Sullivan, 1988).

QFD is generated to focus on project budgets in terms of quality and customers' needs in order to utilize at the early phases of a project to make more proper decisions (Malon et al., 1993).

Even at first in order to determine a methodic approach for production process was evolved as QFD, it can either be utilized to methodically develop requirements of any service, product or system from a bunch of necessities (Azadi et al., 2013).

The power of this method lies in giving precedence and explaining information to be translated from the requirement phase to the properties phase (Kumar et al., 2001). QFD has widely and effectively been applied in many selection processes as follows: Pharmaceutical industry: (Alinezad et al., 2013); Dairy industry: (Ayağ et al., 2012); Housing projects in construction industry: (Dikmen et al., 2005); Interested readers can find a detailed survey of QFD applications in Azadi et al. (2013).

QFD is executed by providing detailed guidance throughout the service development process called House of Quality (HoQ) which is a combination of sub-matrices (Cohen, 1995). The HoQ includes six main parts as shown in Fig.3-2; needs of customers, technical measures, planning matrix, relationship matrix, correlation matrix and the lastly weights, benchmarks and targets. The first matrix is WHATs section, the technical measures are listed in section II as HOWs and the degree of relationship between needs of customers and technical measures are measured in matrix IV. Matrix III is used for planning and benchmarking. The relationship has four levels; no-relationship, weak, medium, and strong and four symbols described in Fig.3-1 and there is no symbol for no-relationship. In the literature these symbols are transformed into numbers using a measurement scale respectively; 0 for no-relationship, 1 for weak relationship, 3 for medium relationship, 9 for strong relationship. The technical correlation matrix V is for the interrelated technical measures. The absolute and relative importance of technical measures is calculated in matrix VI. (Azadi et al., 2013)

Relationships	
Strong	●
Moderate	○
Weak	▽

Figure 3-1 The relationship symbols

Let d_{ij} be the relationship importance of j^{th} technical measure by i^{th} customer requirement, c_j be the j^{th} customer importance ratio (weight) and t_i be the i^{th} technical measure importance;

$$t_i = \sum_{j=1}^{n} d_{ij} c_i \qquad \forall \quad i = 1, 2, \ldots, m \tag{2}$$

The technical importance ratio (weight) w_i ;

$$w_i = \frac{t_i}{\sum_{i=1}^{m} t_i} \qquad \forall \quad i = 1, 2, \ldots, m \tag{3}$$

The normalization of customer importance ratings;

$$c_j = \frac{a_j}{\sum_{j=1}^{n} a_j} \qquad \forall \quad j = 1, 2, \ldots, n \tag{4}$$

where a_j be the j^{th} customer importance and the calculation of c_j.

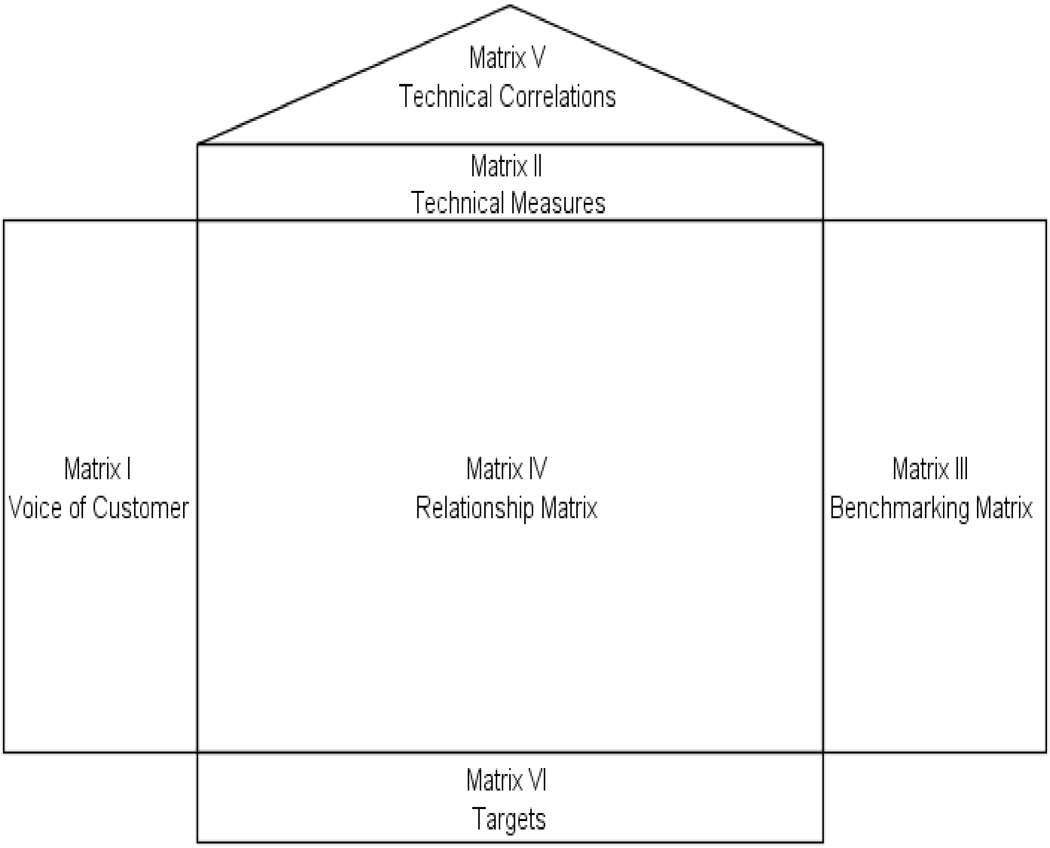

Figure 3-2 Structure of HOQ

Even QFD is used for service development and product design we use this method to help us considering customer requirements and expectations which are drivers and pedestrians for roadway lighting.

3.4 A Brief overview on SAW methodology

In consequence of this method's simplicity and easiness, SAW is one of the most common and extensively used methods in MCDM according to Shakouri et al (2014) and it is found and expressed firstly by Edwards in 1971. Additive aggregation of decision scores or consequences is regulated by weights stating the importance of criteria in this method.

A total score in the SAW is computed by adding the contributions from each attribute. Each value of the attributes is numerical to compare among them. Since two items with different measurement units cannot be added, normalization is needed to allow addition among attribute values. The total score for each alternative can be computed by multiplying the normalized value of each attribute for the alternatives with the weight of the attribute and then summing these products over all the attributes (Yoon et al., 1995).

The alternative with the maximum score is selected as the preferred one for MCDM problems. Assume that the number of alternatives is n and the number of criteria is m and the total score of an alternative is expressed as follows:

Let the S_i be the total score of the i^{th} alternative, the calculation of the total score is as shown as follows:

$$S_i = \sum_{j=1}^{m} w_j r_{ij} \quad \forall\ i = 1,\ldots,n \tag{5}$$

where w_j is the weight of the j^{th} criteria; x_{ij} is the original value of the j^{th} criteria of i^{th} alternative; r_{ij} is the normalized value j^{th} criteria of i^{th} alternative which is calculated as follows:

For benefit;

$$r_{ij} = \frac{x_{ij}}{(\max_i x_{ij})} \tag{6}$$

for cost:

$$r_{ij} = \frac{\left(\frac{1}{x_{ij}}\right)}{\left[\max_i \left(\frac{1}{x_{ij}}\right)\right]} \tag{7}$$

In addition to simplicity of this method the decision model does not rely on the alternatives according to Brownlow et al. (1987). If there is a need to add new alternatives or attributes to the existing model this being absolute is very important and there is no requirement for any new evaluation and can proceeded from the former scores in the assessment procedure (Akgun et al., 2010).

Because of all noticed above, the SAW method is the easiest and the most suitable MCDM method to normalize the DEA values and compute the overall score of the roadway lighting alternatives to rank the these alternatives by ranking them.

4 METHODOLOGY FOR THE PROPOSED APPROACH

4.1 Introduction

Roadway lighting selection is a complicated process because of the relevant inputs and outputs to the process that is a complex decision making with external and internal factors. The DEA is an effective analysis tool to determine the efficient alternative but not enough to identify the best one and does not involve the customer requirements. However, the QFD comprises the customer needs with the technical attributes which are weighted by customer needs. The SAW is a method to normalize the value of technical attributes for alternatives with the weights and rank the alternatives.

An originally established multi-methodological approach based on the DEA, QFD and SAW to select the best roadway lighting is proposed in this thesis.

4.2 The Proposed Approach

In the proposed approach, roadway lighting installations as DMUs are analyzed by DEA and the efficient roadway lightings are determined. The technical attributes of installations which are outputs of DMUs are applied to the HoQ as HOWs (technical measures) in terms of QFD by the experts' opinions. Then the importance values (importance ratio or weights) of the technical attributes are calculated using QFD method. These importance values are used to calculate overall score of the efficient DMUs as weights by normalizing (standardizing) the rating of the DMUs for the technical attributes. According to these total scores, the DMUs are ranked in terms of SAW method and the best installation for roadway lighting is designated. Finally, the overall DMU scores are evaluated by the proposed approach with the advantages of these methods. Also an evaluation is done to compare cost analysis methods which are reviewed in the literature.

This thesis analyzes the double-side luminaire arrangements and a selected lighting classes for roadway based on the CIE standards. In despite of analyzed one type of roadway lighting classes, this proposed approach is generic method and can be studied and implemented for every type of roadways.

The proposed approach using DEA, QFD and SAW is indicated in the Fig.4-1 and consists of the following steps:

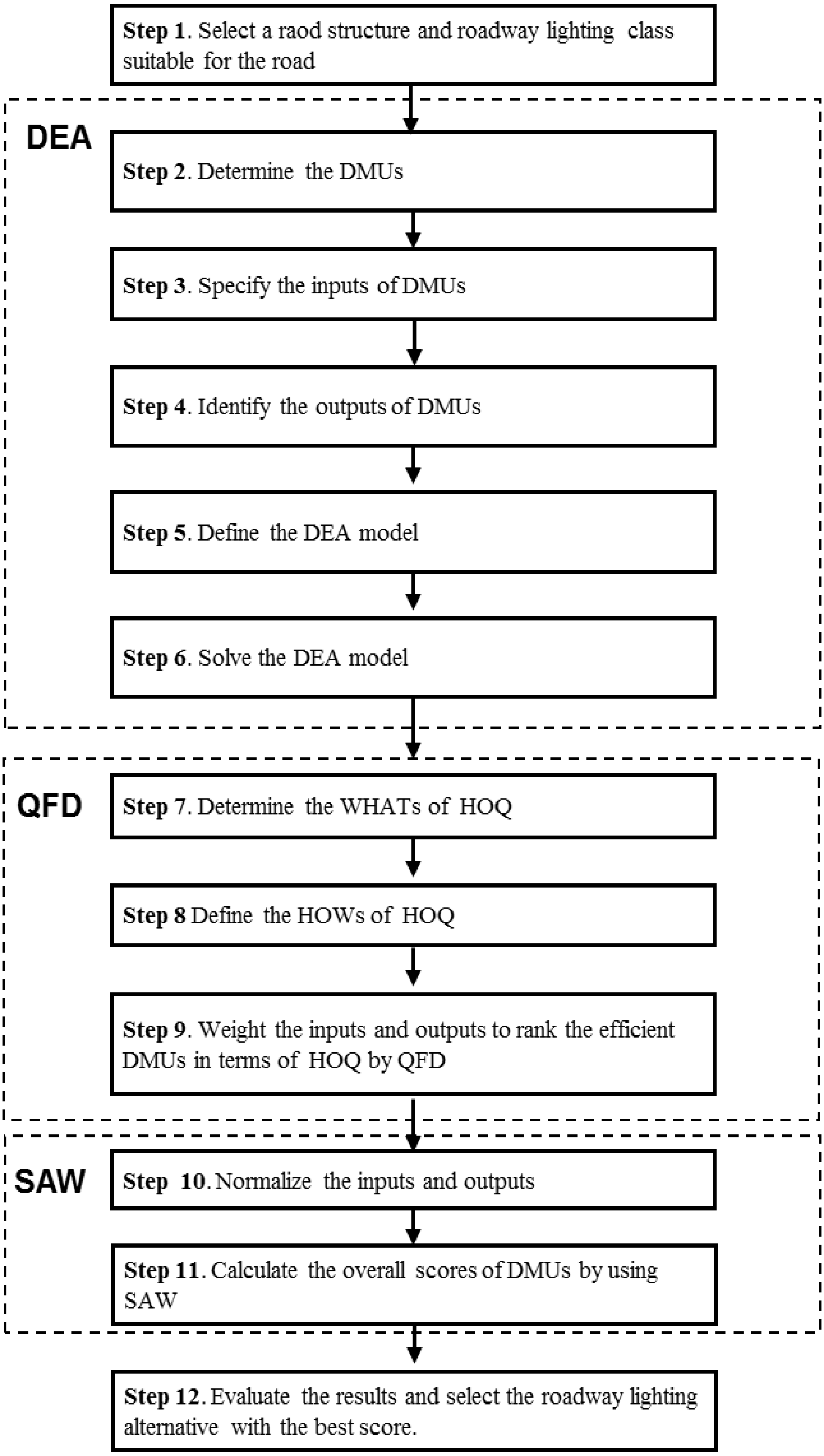

Figure 4-1 The framework of proposed approach

4.2.1 Step 1: Selecting the road structure and roadway lighting class suitable for the road

Select a roadway lighting class and structure of road. The roadway structure and class are chosen to construct the area where roadway lighting installations are implemented based on CIE 115:2010 and CEN/TR 13201-1 and is constructed in simulation optimization lighting software DIALux.

The DIALux is the open source software standard for calculating lighting layouts. The lighting layout can be calculated with the luminaires of the world's leading manufacturers in DIALux. As a result the huge independency is available in the design process. The lighting for both indoor and outdoor can be computed optimally and simulated in DIALux.

4.2.2 Step 2: Determining the DMUs

Determine the DMUs. The installation alternatives of roadway lighting are chosen with regard to roadway lighting class standards and structure as DMUs for efficiency analysis. The selected DMUs are verified in terms of standards by DIALux. The roadway lighting alternatives which meet the standards are chosen as DMUs to be analyzed with DEA.

4.2.3 Step 3: Specifying the inputs of DMUs

Specify the inputs of DMUs. The DEA method minimizes the inputs of DMUs. Because of this, the vulnerabilities and incommodities of alternatives are chosen as inputs of DMUs. The capital cost, the operating cost and the maintenance cost are specified as inputs of roadway lighting alternatives. These inputs are selected from technical brochures and specifications as raw data and are calculated by the following equations;

Let $N_{p,i}$ be the number of poles for installation *i*, the price of installation *i* is denoted as *pi* and capital cost (*CC)* is calculated as follows:

$$CC = N_{p,i} \times pi \quad (8)$$

where $N_{p,i}$ are calculated according to selected road length, structure and lighting class standards by using the DIALux optimization and the *pi* is taken from the technical brochures.

Let P_i be the total electrical power that the installation *i* uses measured in kilowatt (kW), T_i be the usage time of installation *i* as hour per year and W_i be the total energy consumption of installation *i* (kWh) is calculated as follows:

$$W_i = N_{p,i} \times P_i \times T_i \quad (9)$$

where P_i and T_i are taken from technical brochures.

The price per unit of electricity (*ep*) is measured in Turkish Lira (*TL*) and the operating cost (*OC*) is calculated as follows:

$$OC = W_i \times ep \times 10^{-3} \quad (10)$$

where *ep* is taken from Turkish Electricity Distribution Company (TEDAS) and is determined by governments.

Let *ne* be the number of employers, *dg* be the daily wage, *fc* be the daily fuel consumption measured in money (*TL*), *Nh* be the number of installations which are maintained in an hour, *wh* be the daily working hours and *MC* be the maintenance cost is calculated as below:

$$MC = \frac{(ne \times dg + fc) \times N}{Nh \times wh} \quad (11)$$

4.2.4 Step 4: Identifying the outputs of DMUs

Identify the outputs of DMUs. The DEA method maximizes the outputs of DMUs. Because of this reason benefits, strengths and technical attributes of the alternatives are identified as outputs of DMUs. These technical attributes and strengths are lifetime of lamp, efficacy, luminous flux and lighting which some of these are also requirements for roadway lighting standards.

Before giving the formula and origin of the outputs, there is a need to define purpose of roadway lighting; is to reach a level of visibility which enables the driver and pedestrian to see quickly, clearly, and with certainty all significant detail, obviously the alignment of the road and any obstacles on the roadway as defined in publication of Minnesota Department of Transportation- Roadway Lighting Design Manual. (2010)

Another need to understand formulas is defining roadway lighting terms that are used in this chapter. The light is visually evaluated radiant energy. Visibility is the status of being observable by human eye. Lumen is the amount of light energy produced by a light source. Lights are usually ranked for their efficiency in lumens per watt which is the measurement of the amount of electricity an installation consumes. Luminous intensity (I) is the force of luminous flux in a specified direction, measured in candelas per kilolumen (cd/klm) . Luminous flux (Φ) is time rate flow of light, measured in lumens(lm). Illuminance (E) is the density of luminous flux incident on a road area, measured in lux (lx). Lighting (luminance) is the amount of luminous flux diffused, transmitted or reflected from a road area in a exact direction, measured in lm/m^2. All definitions above are explained in CEN/TR 13201-3. Efficacy is the lighting ratio of luminous flux to the electrical lamp power (lm/W).

Let r be the reduced luminance coefficient for a light path incident, mf be the luminaire maintenance factor, h be the mounting height of the luminaires above the road surface and the calculation of lighting or luminance (L) at a point of road surface is stated as follows:

$$L = \frac{I \times r \times mf \times \Phi \times 10^{-4}}{h^2} \tag{12}$$

Let Φ be the luminous flux of the installation measured in lumen (lm), ε be the efficacy is calculated as below:

$$\varepsilon = \frac{\Phi}{P_i} \tag{13}$$

The life time of lamp and luminous flux are taken from the technical brochures and lighting is calculated and taken from DIALux optimization.

Simulation optimization and verification of the DMUs are done by lighting software (DIALux). The lower bounds of lighting standards are examined by simulating of DMUs technical parameters on DIALux. After the DMU perform the minimum standards of lighting, the DMUs technical parameters (outputs) are verified in terms of standards. The simulation optimize the lighting by using technical parameters as tilt angle, pole distance, power, light center height, light overhang, pole rotation.

The software calculation of illuminance (E) of the installations simulated at the planned surface is stated Eq.(11) where $I(C,\gamma)$ coordinate system with C is the photometric azimuthal angle, γ is the vertical angle and I is the luminous intensity measured in cd/klm (Gómez-Lorente et al., 2013).

The orientation of C, γ coordinate system in relation to longitudinal direction of carriageways is shown at Fig.4-2 where *1* is the luminaire at tilt during measurement, *2* is the longitudinal direction, *3* is the first photometric axis, *4* is the direction of luminous intensity. (CEN/TR 13201-3)

This equation is used by the software for optimization and verification to compare the DEA software results.

$$E = \frac{\Phi}{1000} \sum \frac{I(C,\gamma)}{h^2} \cos^3 \gamma \qquad (14)$$

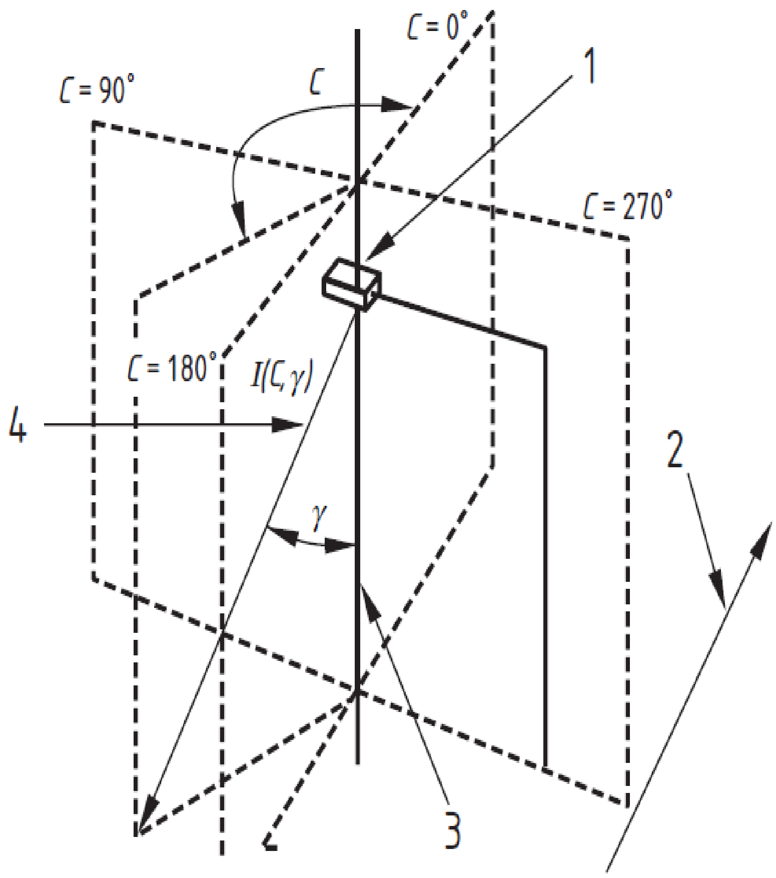

Figure 4-2 Orientation of C, γ coordinate system in relation to longitudinal direction of carriageways (CEN/TR 13201-3)

4.2.5 Step 5: Defining the DEA model

Define the DEA model. The type of DEA model is defined by the properties of roadway lighting alternatives. This model is selected input oriented CCR DEA model to minimize the costs as inputs with the fixed technical standards. The model minimizes the inputs with constant outputs to produce an efficiency measure for DMUs. (Lotfi et al., 2010)

The input oriented CCR DEA model is the most suitable model for cost and energy efficient and also sufficient lighting because of cost and energy consumption minimization.

Assume that there is a group of n DMUs ($i = 1, 2, ..., n$) which are evaluated for all variables where x_{ij} is the quantity of j th input of i th DMU, θ is the efficiency measure, λ is the weight for DMUs in the analyses process (Khezrimotlagh et al., 2010).

Then the input oriented CCR DEA model is as follows:

$$\min \theta$$

subject to

$$\sum_{i=1}^{n} \lambda_i x_{ij} \leq \theta x_{dj} \quad \forall j = 1,\dots,l$$

$$\sum_{i=1}^{n} \lambda_i y_{ik} \geq y_{dk} \quad \forall k = 1,\dots,s$$

$$\lambda_i \geq 0 \quad \forall i = 1,\dots,n \qquad (15)$$

4.2.6 Step 6: Solving the DEA model

Solve the DEA model. The Open Source DEA software (OSDEA-GUI-v0.2) searches for the points with the any given variable, connecting those points to form the efficiency frontier.

Each DMU is evaluated in terms of input oriented CCR (CRS) model by OSDEA. The OSDEA calculates the DEA technical efficiency scores (θ) for each roadway lighting alternatives by employing CCR (CRS) input oriented DEA formulation. The efficient roadway lighting alternatives are determined with an efficiency score of 1.

The OSDEA-GUI-v0.2 is an open-source program which solves Data Envelopment Analysis problems as defined in opensourcedea web page.

4.2.7 Step 7: Determining the WHATs of HoQ

Determine the WHATs of HoQ. The first matrix of HoQ is the WHATs section as customer requirements and also known as Voice of Customer (VoC). These are the expectations and needs of customer from a service or product as WHAT customers need and expect to transform customer requirements into engineering attributes. The WHATs which are constituents of first matrix of HoQ, are commonly derived in the customers' personal words. (Hauser et al., 1988).

This section is very important to reflect customer requirements on the products or service projects. In this thesis roadway lighting alternative selection is can be defined as a service project that the customers of it are citizens in a country or municipality, students in a university, officers in a base as drivers or pedestrians. There are many ways to determine the WHATs as questionnaire, opinion survey, market research or establishing a group of customers on the purpose of learning needs. In this thesis we establish a small group of drivers and pedestrians whom are our partners at work and asked their expectations and requirements for roadway lighting.

4.2.8 Step 8: Defining the HOWs of HoQ

Define the HOWs of HoQ. The second matrix of HoQ is the HOWs section as technical measures or attributes for understanding the consumer claims (Benner et al., 2003). These are the technically determined quality characteristics by specifications, regulations, technical brochures and experts. In order to determine the HOWs section we need to review and analyze and advise with the technical experts.

4.2.9 Step 9: Weighting the outputs and inputs to rank the efficient DMUs

Weight the outputs and inputs to rank the efficient DMUs in terms of HoQ by QFD. Firstly customer needs are designated by experts and the relationships between the technical attributes and customer needs are established for weighting them. The customer ratings (5 high, 1 low) are normalized and multiplied to the relations of customer needs for each technical attribute to compute the importance of the technical attributes. Then these importance scores are normalized as importance ratios (weights) for SAW. After the definition of relationships, the weights of technical attributes and customer needs are used for ranking the alternatives. The relationship signs where (●) is 9 points; (○) is 3 points and (▽) is 1 point, are illustrated in Fig.4-3.

Relationships	
Strong	●
Moderate	○
Weak	▽

Figure 4-3 Relationship signs for HOQ

Let d_{ij} be the relationship importance of j^{th} technical measure by i^{th} customer requirement, c_j be the j^{th} customer importance ratio (weight) and t_i be the i^{th} technical measure importance;

$$t_i = \sum_{j=1}^{n} d_{ij} c_i \qquad \forall \quad i = 1, 2, ..., m \tag{16}$$

The technical importance ratio (weight) w_i ;

$$w_i = \frac{t_i}{\sum_{i=1}^{m} t_i} \qquad \forall \quad i = 1, 2, ..., m \tag{17}$$

The normalization of customer importance ratings;

$$c_j = \frac{a_j}{\sum_{j=1}^{n} a_j} \qquad \forall \quad j = 1, 2, ..., n \tag{18}$$

where a_j be the j^{th} customer importance and the calculation of c_j.

4.2.10 Step 10: Normalizing the inputs and outputs by using SAW

Normalize the inputs and outputs by using SAW. The inputs and outputs are normalized for each DMU in terms of SAW by using Eq.(3, 4). The benefits of this normalization are; obtaining comparable scales and dimensionless units to compare the elementarily.

Let w_j be the weight of the j^{th} input or output, x_{ij} be the original value of the j^{th} input or output of i^{th} DMU, r^{ij} be the normalized value j^{th} input or output of i^{th} DMU which is calculated for benefit as r_{ij} = x_{ij}/(max$_i$ x_{ij}) and for cost as r_{ij} = (1/x_{ij})/[maxi (1/x_{ij})].

4.2.11 Step 11: Calculating the overall scores of DMUs by using SAW

Calculate the overall scores of DMUs by using SAW. The overall scores are calculated to rank the DMUs by using the weights from QFD in terms of SAW.

Let the OS_i be the overall score of the i^{th} DMU is calculated as follows Eq.(5):

$$OS_i = \sum_{j=1}^{m} w_j r_{ij} \quad \forall \text{ i}= 1,\ldots,n \tag{19}$$

4.2.12 Step 12: Evaluating the results

Evaluate the results and select the roadway lighting alternative with the best score. Furthermore, the effects of variables are presented and discussed.

The detailed descriptions of each step are elaborated in the following illustrative case study chapter.

5 CASE STUDY

In this section, the proposed approach of DEA, QFD and SAW as explained in Chapter 4 is implemented to an assumed university campus road which executives are confronted by the roadway lighting selection problem. The selected roadway was a motorway with limited speed in a green campus which is sustainable energy and resource efficient campus with improving energy efficiency, protecting resources and improving environmental feature by educating for sustainability and creating healthy living and learning environments. (Tan et al., 2014)

The current roadway lightings can be categorized into four main technologies; HPS lamps, HPM lamps, MH lamps and LED as well. Because of listed reasons only HPS and LED lamps are studied for selected urban road and its specific lighting class in this study; regulations, forbidden/unused lamps as well. Due to the different results of implementation procedures of both types of lamps, some advantages, disadvantages, opportunities and challenges have been appeared.

An example of HPS lamps is indicated in Fig.5-1;

Figure 5-1 An example of HPS lamp

An example of HPS installation is indicated in Fig.5-2;

Figure 5-2 An example of HPS installation

An example of LED is indicated in Fig.5-3;

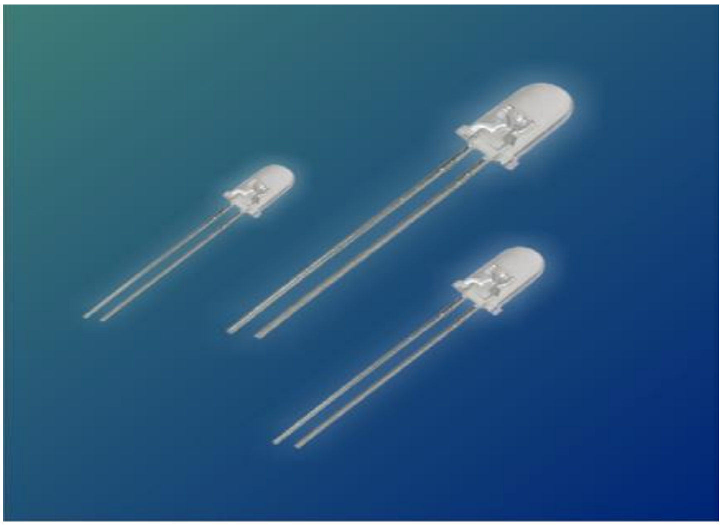

Figure 5-3 An example of Lighting Emitting Diode

An example of LED installations is indicated in Fig.5-4;

Figure 5-4 An example of LED installation

It may be remarked that all values in this study are actual data and the up to date were taken from technical brochures and technical prescriptions. The proposed model for roadway lighting selection problem was built as follows:

5.1 Step 1: Selecting the road structure and roadway lighting class suitable for the road

First of all in this case study roadway structure was constructed as double side luminaire arrangement to analyze. The length of the road is 1000 m, the width of the road is 14 m; 3.5 m for each lane. The lighting class of chosen road is M4 based on CIE 115:2010 and CEN/TR 13201-1 and was applied in simulation optimization lighting software DIALux. An example of this verification simulation and road structure is shown in Fig.5-5, Fig.5-6 and Fig.5-7;

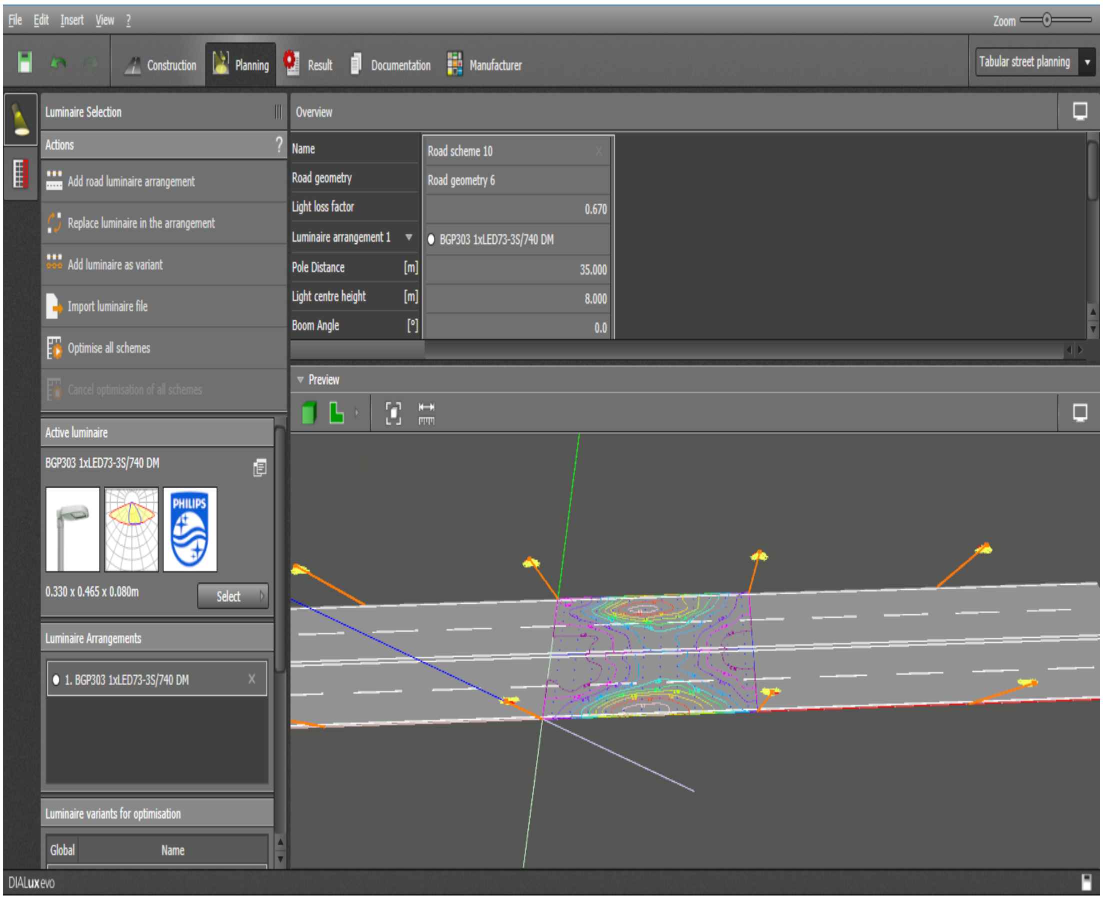

Figure 5-5 A structured roadway with lightings in DIALux simulation

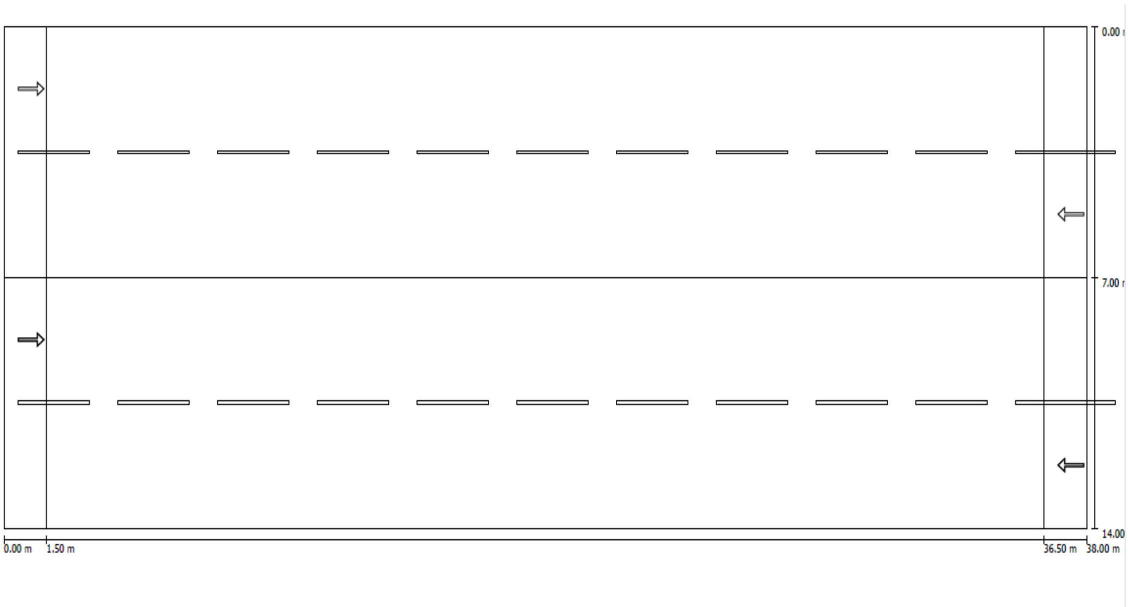

Figure 5-6 The selected double-sided roadway

Araç yolu 1 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 10 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 1	Width: 7.000 m Number of Lanes: 2 Surface (dry): CIE R3 q0 (dry): 0.070 Surface (wet): Wet surface W3 q0 (wet): 0.200

	Lm [cd/m²]	U0	Ul	TI [%]	SR
Actual value according to calculation	2.38	0.51	0.75	5	0.79
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-7 An output of DIALux simulation

5.2 Step 2: Determining the DMUs

In DMU selection process, technical brochures, technical prescriptions and directives were examined to select the common use technologies and allowed ones by governments. More than a hundred alternatives were searched and were verified in terms of standards by DIALux. The roadway lighting alternatives which met the standards were chosen as DMUs to be analyzed with DEA. Eight installation alternatives of both HPS and LED were chosen with regard to M4 roadway lighting class standards as DMUs for efficiency analysis. These were named as HPS1, HPS2, HPS3, HPS4 and LED1, LED2, LED3, LED4.

These selected roadway lighting alternatives were proven with regards to technical sufficiency and optimal lighting efficiency by DIALux. The technical results and lighting isolines as outputs were shown as follows (the outputs were illustrated as screen shots to show the results were not changed by the author). The lighting isolines show the lighting distribution on the selected road surface to check if roadway is sufficiently lit or not. The technical results show if the selected roadway lighting satisfy the roadway lighting standards or not.

Table 5-1 Technical parameters of DMUs from DIALux

DMU	Power (W)	Pole Distance (m)	Light Centre Height (m)	Max.Luminous Intensity at 70° (cd/klm)	Max.Luminous Intensity at 80° (cd/klm)
HPS1	276	28	8	388	57
HPS2	4334	32	8	318	37
HPS3	276	28	8	286	9.19
HPS4	433	35	8	242	9
LED1	58	35	8	605	48
LED2	81	35	8	594	47
LED3	56	33	8	520	30
LED4	85	35	8	512	29

Araç yolu 3 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 10 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 3

Width: 7.000 m
Number of Lanes: 2
Surface (dry): CIE R3
q0 (dry): 0.070
Surface (wet): Wet surface W3
q0 (wet): 0.200

	Lm [cd/m²]	U0	Ul	TI [%]	SR
Actual value according to calculation	3.53	0.73	0.72	11	0.81
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-8 Result summary of HPS1 verification in DIALux

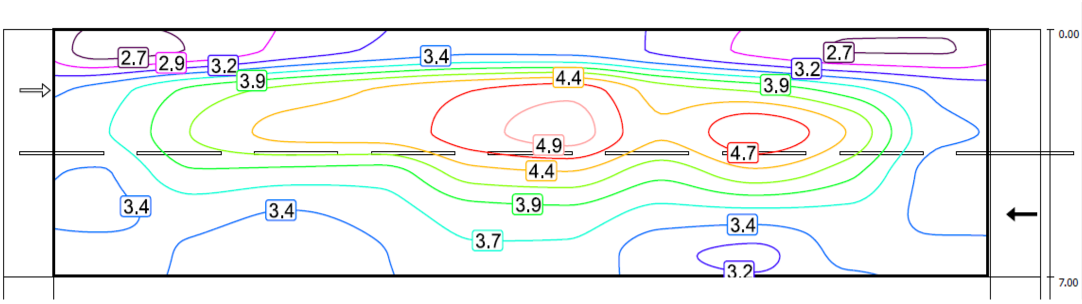

Figure 5-9 Lighting isolines results of HPS1in DIALux

As can be seen above the first DMU HPS1 was verified in DIALux and all roadway lighting standards were satisfied by HPS1.

Araç yolu 1 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 11 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 1	Width: 7.000 m Number of Lanes: 2 Surface (dry): CIE R3 q0 (dry): 0.070 Surface (wet): Wet surface W3 q0 (wet): 0.200

	Lm [cd/m²]	U0	UI	TI [%]	SR
Actual value according to calculation	5.41	0.72	0.62	/	0.79
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-10 Result summary of HPS2 verification in DIALux

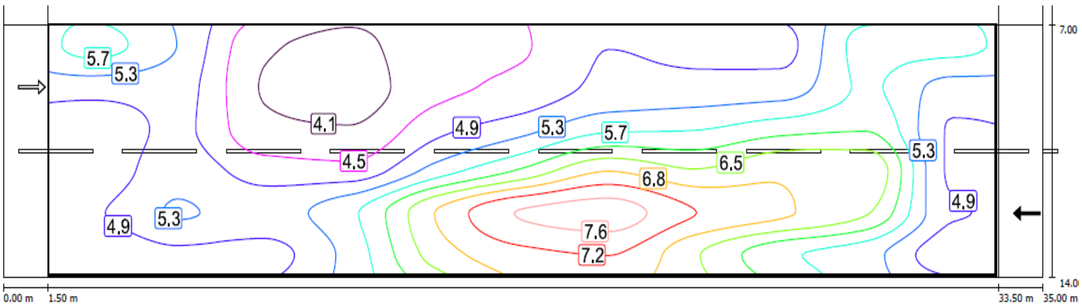

Figure 5-11 Lighting isolines results of HPS2 in DIALux

As can be seen above the second DMU HPS2 was verified in DIALux and all roadway lighting standards were satisfied by HPS2.

Araç yolu 1 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 10 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 1

Width: 7.000 m
Number of Lanes: 2
Surface (dry): CIE R3
q0 (dry): 0.070
Surface (wet): Wet surface W3
q0 (wet): 0.200

	Lm [cd/m²]	U0	UI	TI [%]	SR
Actual value according to calculation	2.38	0.51	0.75	5	0.79
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-12 Result summary of HPS3 verification in DIALux

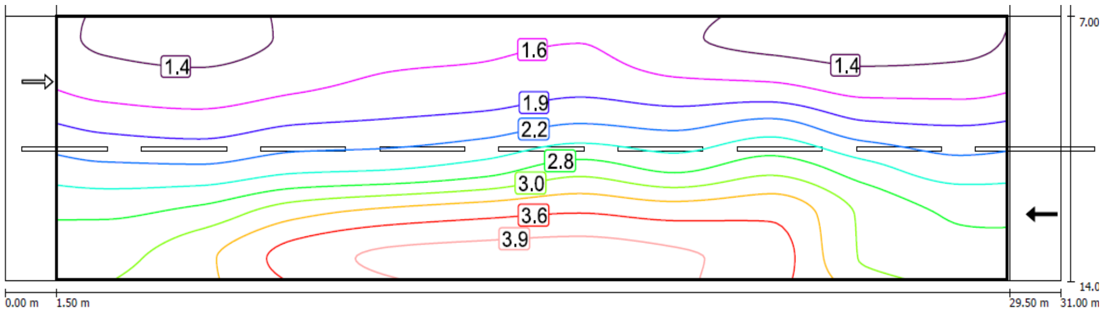

Figure 5-13 Lighting isolines results of HPS3 in DIALux

As can be seen above the third DMU HPS3 was verified in DIALux and all roadway lighting standards were satisfied by HPS3.

Araç yolu 2 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 12 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 2	Width: 7.000 m Number of Lanes: 2 Surface (dry): CIE R3 q0 (dry): 0.070 Surface (wet): Wet surface W3 q0 (wet): 0.200

	Lm [cd/m²]	U0	Ul	TI [%]	SR
Actual value according to calculation	3.69	0.64	0.63	13	0.81
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-14 Result summary of HPS4 verification in DIALux

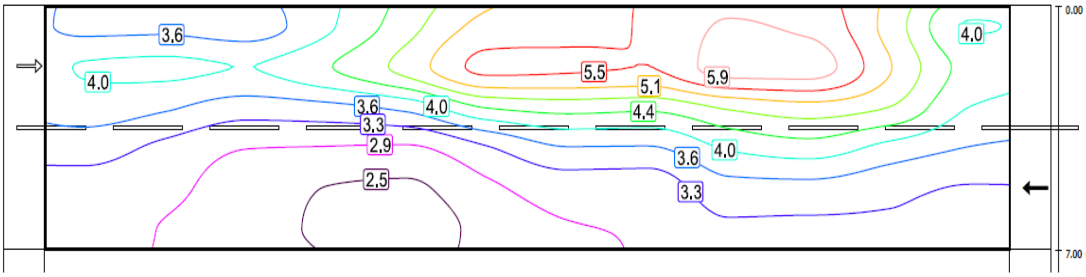

Figure 5-15 Lighting isolines results of HPS4 in DIALux

As can be seen above the fourth DMU HPS4 was verified in DIALux and all roadway lighting standards were satisfied by HPS4.

Araç yolu 2 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 12 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 2	Width: 7.000 m Number of Lanes: 2 Surface (dry): CIE R3 q0 (dry): 0.070 Surface (wet): Wet surface W3 q0 (wet): 0.200

	Lm [cd/m²]	U0	Ul	TI [%]	SR
Actual value according to calculation	0.77	0.71	0.60	13	0.86
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-16 Result summary of LED1 verification in DIALux

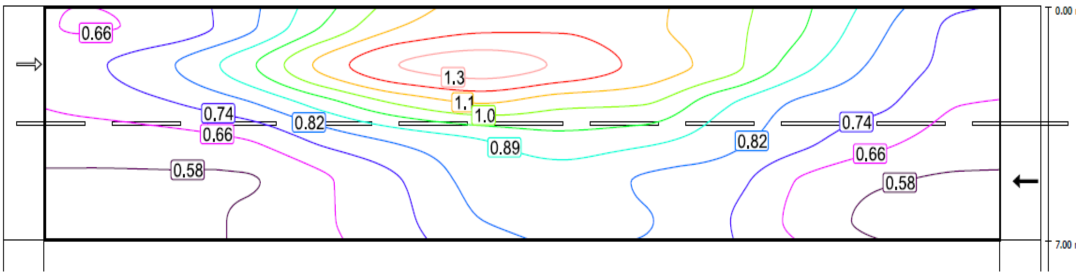

Figure 5-17 Lighting isolines results of LED1 in DIALux

As can be seen above the fifth DMU LED1 was verified in DIALux and all roadway lighting standards were satisfied by LED1.

Araç yolu 2 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 12 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 2

Width: 7.000 m
Number of Lanes: 2
Surface (dry): CIE R3
q0 (dry): 0.070
Surface (wet): Wet surface W3
q0 (wet): 0.200

	Lm [cd/m²]	U0	Ul	TI [%]	SR
Actual value according to calculation	1.01	0.71	0.60	14	0.86
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-18 Result summary of LED2 verification in DIALux

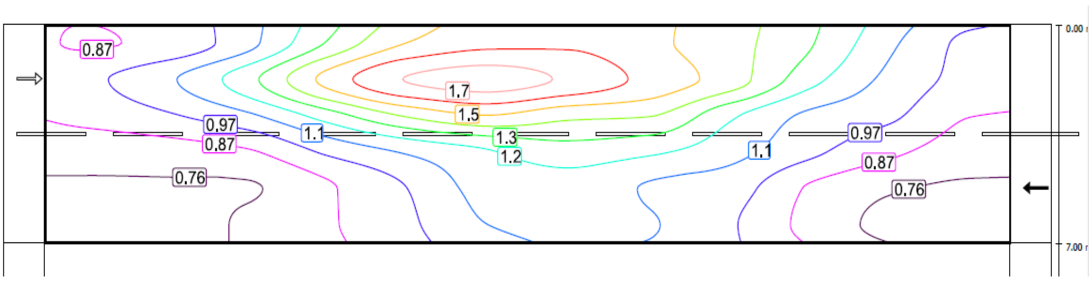

Figure 5-19 Lighting isolines results of LED2 in DIALux

As can be seen above the sixth DMU LED2 was verified in DIALux and all roadway lighting standards were satisfied by LED2.

Araç yolu 2 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 11 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 2	Width: 7.000 m Number of Lanes: 2 Surface (dry): CIE R3 q0 (dry): 0.070 Surface (wet): Wet surface W3 q0 (wet): 0.200

	Lm [cd/m²]	U0	UI	TI [%]	SR
Actual value according to calculation	0.76	0.72	0.69	12	0.87
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-20 Result summary of LED3 verification in DIALux

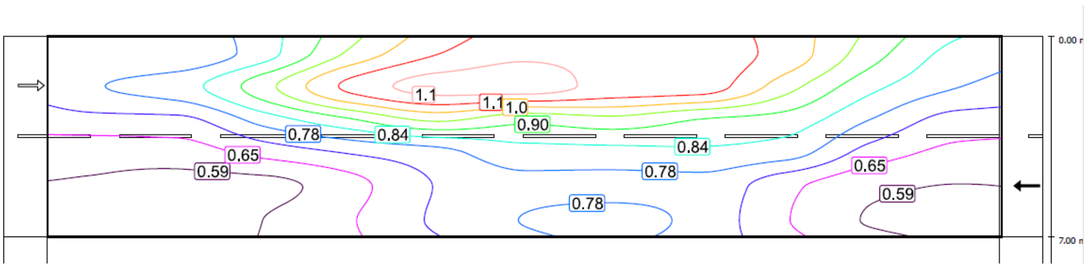

Figure 5-21 Lighting isolines results of LED3 in DIALux

As can be seen above the seventh DMU LED3 was verified in DIALux and all roadway lighting standards were satisfied by LED3.

Araç yolu 2 (ME4a) / Results summary

Light loss factor: 0.67
Grid: 12 x 6 Points
Selected Lighting Class: ME4a
Accompanying Street Elements:

Roadway 2	Width: 7.000 m Number of Lanes: 2 Surface (dry): CIE R3 q0 (dry): 0.070 Surface (wet): Wet surface W3 q0 (wet): 0.200

	Lm [cd/m²]	U0	UI	TI [%]	SR
Actual value according to calculation	1.04	0.69	0.62	13	0.87
Required values according to class	≥ 0.75	≥ 0.40	≥ 0.60	≤ 15	≥ 0.50
Fulfilled/Not fulfilled	✓	✓	✓	✓	✓

Figure 5-22 Result summary of LED4 verification in DIALux

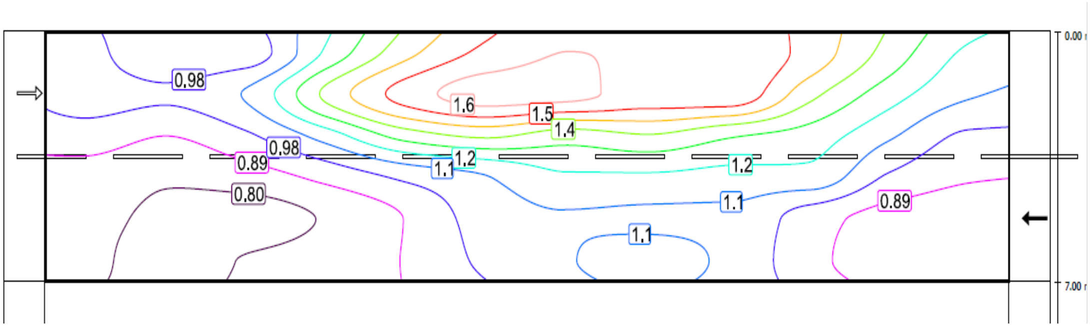

Figure 5-23 Lighting isolines results of LED3 in DIALux

As can be seen above the eighth DMU LED4 was verified in DIALux and all roadway lighting standards were satisfied by LED4.

5.3 Step 3: Specifying the inputs of DMUs

The capital cost, operating cost and maintenance cost were specified as inputs of the model. The data of the selected inputs were taken brochures and were calculated by Eq.(8,9,10,11) and were shown in Table 5-1.

The calculations is given one for each input for the HPS1 as follows :

$CC =$ 1094,4 x 72 = 78796,8 TL

W_i = 72 x 276 x 4326 = 85966272 Wh

OC = 85966272 x 0,25 x 10^{-3} = 21491,568 TL

$$MC = \frac{(6\times150+212)\times72}{3\times8} = 3337\,TL$$

5.4 Step 4: Identifying the outputs of DMUs

The outputs of DMUs were identified as the technical attributes and strengths which were lifetime of lamp, efficacy, luminous flux and lighting. The some data of the selected outputs were taken brochures and some were calculated by Eq.(13) and were shown in Table 5-1.

$$\varepsilon = \frac{28220}{276} = 102{,}24\ lm/W$$

Simulation optimization and verification of the DMUs were done by DIALux. The lower bounds of lighting standards were examined by simulating of DMUs technical parameters used Eq.(14) on DIALux. An example of this verification is shown in Fig.5-7;

Table 5-2 Input and output values of DMUs

	INPUTS			OUTPUTS			
DMU	**Capital Cost (TL)**	**Operating Cost (TL)**	**Maintenance Cost (TL)**	**Lifetime of Lamp (hours)**	**Efficacy (lm/w)**	**Luminous Flux (lm)**	**Lighting (cd/m^2)**
HPS1	78796.8	21491.568	3337	12000	102.24	28220	3.52
HPS2	68486.4	27160.791	2679	12000	114.82	49720	5.41
HPS3	47174.4	21491.568	3337	15000	75.07	20720	2.38
HPS4	42282	27160.791	2679	15000	82.03	35520	3.69
LED1	89954.52	3638.166	114	60000	110	6378	0.77
LED2	89954.52	5080.887	114	50000	103	8342	1.01
LED3	102897	3633.84	120	60000	114	6407	0.76
LED4	110136.78	5331.795	114	60000	110	9381	1.04

5.5 Step 5: Defining the DEA model

The input oriented CCR DEA model was defined with regards to the properties of roadway lighting alternatives according to Eq.(15) and the model structure was shown in Fig.5-24.

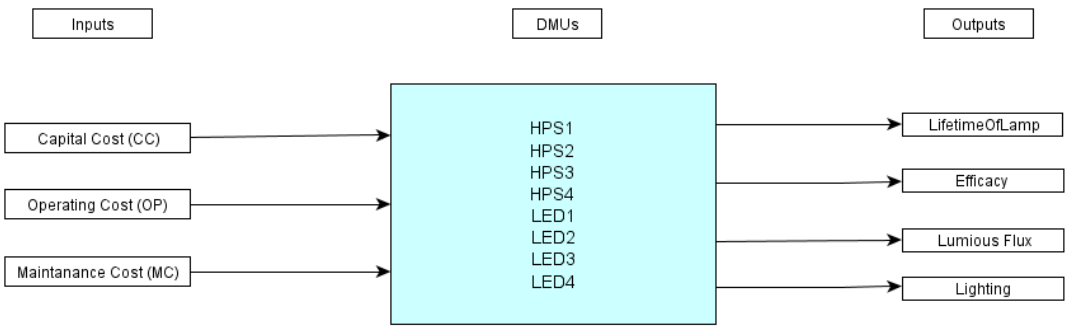

Figure 5-24 The DEA model structure

5.6 Step 6: Solving the DEA model

The structured input oriented DEA model was solved by OSDEA-GUI. The efficiency scores (θ) of each DMU were calculated and evaluated in terms of input oriented CCR (CRS) model by OSDEA. The efficient roadway lighting alternatives were determined with an efficiency score of 1. The DMUs with efficiency score of 1 illustrated in Table 5-2.

Table 5-3 Efficiency Scores of DMUs

DMUs	Efficiency Scores
HPS1	0.854
HPS2	1
HPS3	0.952
HPS4	1
LED1	1
LED2	1
LED3	1
LED4	1

HPS2, HPS4, LED1, LED2, LED3 and LED4 were determined efficient and HPS1, HPS2 were inefficient according to this model. Even the capital cost is very high for LED alternatives, all the selected LED alternatives were efficient.

5.7 Step 7: Determining the WHATs of HoQ

The customer requirements for roadway lighting selection were determined as WHATs of HoQ. These requirements were determined by an established small group own words of expectations and needs (VoC) for roadway lighting. Identified customer requirements are as follows:

- Fair Price; is the money that customers pay for roadway lighting as invoice, initial purchase price etc…
- Durable; is about the installation lifetime and durability.
- Efficient; is about how much electricity is consumed by the installation.
- Sufficient Lighting; is related to lighting level of roadway.
- Maintainability; is about easy, cheap and fast maintenance of installation.
- Aesthetic Design; is related to customer pleasure about roadway lighting and design of installation. What type of installation customer want to see on roadway.
- Environment Friendly; is about electricity consumption and durability. Less energy consumption with durable installation.

5.8 Step 8: Defining the HOWs of HoQ

The technical attributes of a roadway lighting installation were defined as HOWs of HoQ. In order to define these attributes the technical brochures of installations were searched and the searched data was consulted with experts about roadway lighting. And also in order to evaluate and rank the DEA efficient DMUs the inputs and outputs were selected as technical measures. These technical measures are as follows:

- Capital Cost; the initial purchase cost of installation.
- Operating Cost; the annual expense or cost of electricity or power used by the installation.
- Maintenance Cost; the expenses associated with keeping a roadway lighting installation in good condition by regularly.
- Lifetime of Lamp; the period of time that roadway lighting installation lasts, functions and stays effectively in use.

and Efficacy, Luminous Flux and Lighting that were defined in the first chapter.

5.9 Step 9: Weighting the outputs and inputs to rank the efficient DMUs

The outputs and inputs were weighted to rank the efficient DMUs in terms of HOQ by QFD. The fair price, durability, efficiency, lighting sufficiency, maintainability, aesthetic design and friendly environment compatibleness of lighting alternatives were designated as customer needs (WHATs) and the outputs and inputs were defined as technical measures (HOWs) in the former steps. Then the relationships between the technical attributes and customer needs were calculated for weighting them and all were shown in Table 5-4. In order to weight the DMUs; the relationship values which were identified by customers in former steps, were multiplied by the customer importance ratios to calculate the weights of technical attributes. In this thesis the Matrix III (Benchmarking Matrix) and Matrix V (Technical Correlations Matrix) were not established and used due to lack of necessity in this proposed approach. The QFD was just utilized to find out weights of technical attributes with regards to customer needs. That’s why there is no roof of

HOQ in Fig.5-25. The weights (importance ratios) were computed respectively; %21.5 for CC, %17.7 for OC, %15.4 for MC, %12.8 for lifetime of lamp, %11.6 for efficacy, %10.4 for luminous flux and finally %10.6 for lighting.

Table 5-4 The technical attributes weights

Technical Attributes	Weights
Capital Cost	%21.5
Operating Cost	%17.7
Maintenance Cost	%15.4
Lifetime of Lamp	%12.8
Efficacy	%11.6
Luminous Flux	%10.4
Lighting	%10.6

Let d_{ij} be the relationship importance of j^{th} technical measure by i^{th} customer requirement, c_j be the j^{th} customer importance ratio (weight) and t_i be the i^{th} technical measure importance;

$$t_i = \sum_{j=1}^{n} d_{ij} c_i \qquad \forall \quad i = 1, 2, ..., m$$

The technical importance ratio (weight) w_i ;

$$w_i = \frac{t_i}{\sum_{i=1}^{m} t_i} \qquad \forall \quad i = 1, 2, ..., m$$

The normalization of customer importance ratings;

Let a_j be the j^{th} customer importance and the calculation of c_j :

$$c_j = \frac{a_j}{\sum_{j=1}^{n} a_j} \qquad \forall \quad j = 1, 2, ..., n$$

The customer importance ratio of fair price Eq.(18):

$$c_1 = \frac{5}{(5+4+5+3+3+2+2)} = 20.8$$

Maintenance cost importance ratio Eq.(11);

$$t_i = \left[(20.8)\times 3 + (16.6)\times 9 + (20.8)\times 3 + (12.5)\times 1 + (12.5)\times 9 + (8.3)\times 1 + (8.3)\times 9\right] = 482$$

and the technical importance ratio (weight) w_i Eq.(15);

$$w_1 = \frac{482}{(482+332+362+673+549+399+324)} = 0.154$$

Customer Requirements \ Technical Measures	Maintenance Cost	Lighting	Efficacy	Capital Cost	Operating Cost	Lifetime of Lamp	Luminous Flux	Customer Rating (5 High, 1 Low): Customer Importance	Importance Ratio %
Fair Price	○		○	●	○	○		5	20.80%
Durable	●			●	●	●		4	16.60%
Efficient	○	●	●	●	●		●	5	20.80%
Sufficient Lighting	▽	●	○	▽	○		●	3	12.50%
Maintainability	●			○	○	●		3	12.50%
Aesthetic Design	▽	▽		●				2	8.30%
Environment Friendly	●	○	●	○	●	●	○	2	8.30%
Importance	482	333	362	673	549	399	324		
Importance Ratio%	15.4	10.6	11.6	21.5	17.7	12.8	10.4		

Figure 5-25 The HoQ for Roadway Lighting Selection

5.10 Step 10: Normalizing the inputs and outputs by using SAW

The inputs and outputs were normalized for each DMU Eq.(6, 7). The normalized input and output values of DMUs which were computed via SAW were represented in Table 5-4. This calculation were done for each input and output of every DMUs so the normalized values of every input and output made be ready to compare with dimensionless scales.

The calculation of normalized value of the first input of first DMU is shown as follows:

r_{21} = (1/68486.8)/[1/42282] = 0.61733

r_{22} = (1/217160.79)/[1/3633.4] = 0.133

r_{23} = (1/2679)/[1/114] = 0.043

r_{24} = 12000/60000 = 0.2

r_{25} = 114.82/114.82 = 1

r_{26} = 49720/49720 = 1

r_{27} = 5.41/5.41 = 1

Table 5-5 Normalized Input and output values of DMUs

	INPUTS			OUTPUTS			
Weights	**(0.215)**	**(0.177)**	**(0.154)**	**(0.128)**	**(0.116)**	**(0.104)**	**(0.106)**
DMU	**Capital Cost**	**Operating Cost**	**Maintenance Cost**	**Lifetime of Lamp**	**Efficacy**	**Luminous Flux**	**Lighting**
HPS2	0.617	0.133	0.043	0.2	1	1	1
HPS4	1	0.133	0.043	0.25	0.714	0.714	0.68
LED1	0.47	0.998	1	1	0.958	0.129	0.143
LED2	0.47	0.715	1	0.833	0.987	0.168	0.187
LED3	0.41	1	0.95	1	0.992	0.129	0.141
LED4	0.39	0.681	1	1	0.958	0.189	0.192

5.11 Step 11: Calculating the overall scores of DMUs by using SAW

The inputs and outputs were normalized for each DMU and then computed the overall scores of DMUs by using Eq.(19) to rank the DMUs. The overall scores of DMUs which were computed by using SAW were illustrated in Table 4.

The calculation of the overall score of first DMU are shown as follows:

$$OS_2 = \left[(w_1 \times r_{21}) + (w_2 \times r_{22}) + (w_3 \times r_{23}) + (w_4 \times r_{24}) + (w_5 \times r_{25}) + (w_6 \times r_{26}) + (w_7 \times r_{27})\right]$$

$$OS_2 = \left[(0.215 \times 0.61733) + (0.177 \times 0.133) + (0.154 \times 0.043) + (0.128 \times 0.2) + (0.116 \times 1) + (0.104 \times 1) + (0.106 \times 1)\right]$$

The overall scores of DMUs which were computed via SAW were represented in Table 5-6.

Table 5-6 Overall scores of DMUs

DMUs	**Overall Scores**
HPS2	0.4925
HPS4	0.5046
LED1	**0.6993**
LED2	0.6388
LED3	0.6828
LED4	0.6369

5.12 Step 12: Evaluating the results

The results are evaluated in terms of DEA-QFD-SAW integrated method and the LED1 roadway lighting alternative which is LED installation, is selected according to the its overall score. Even it is initially more expensive than the HPS alternatives, it has the best overall score according to proposed approach presented in Chapter 4 and examined due to technical attributes weights in this chapter.

The technical attributes have influence on roadway lighting alternative selection due to their importance ratios as shown in Table 5-7 respectively.

Table 5-7 The importance ratios of technical attributes

Technical Attributes	**Importance Ratio**
Capital Cost	0.215
Operating Cost	0.177
Maintenance Cost	0.154
Lifetime of Lamp	0.128
Efficacy	0.116
Lighting	0.106
Luminous Flux	0.104

Table 5-8 Total Costs of DMUs

DMUs	**Total Cost**
HPS3	72002.968
HPS4	72121.791
LED1	93706.686
LED2	95149.407
HPS2	98326.191
HPS1	103625.368
LED3	106650.84
LED4	1115582.575

Table 5-8 represents the total costs of DMUs from the cheapest alternative to the most expensive alternative respectively. According to proposed approach analysis in this thesis the cheap is better is not realistic in terms of sufficiency and efficiency. Also as presented Table 5-9, the capital cost which is thought the most important decision criteria for many people, is not as important as for roadway lighting according to results of the proposed approach. Because the operating cost, maintenance cost, life time and durability are also significant as capital cost. Additionally the chart diagram of all costs of DMUs were separately indicated in Fig.5-26 to compare with the calculated total scores of DMUs in Fig.5-27.

Furthermore, the customer requirements are highly important for a selection problem as seen in this thesis.

Table 5-9 Capital Costs of DMUs

DMUs	Capital Cost
HPS4	42282
HPS3	47174.4
HPS2	68486.4
HPS1	78796.8
LED1	89954.52
LED2	89954.52
LED4	110136.78
LED3	1102897

Finally, the result comparison matrix is stated in Table 5-10 and as can be seen in the table and the study; the selection problems have very complex disciplines and for this reason the multi-methodological method is a must for that kind of problems.

Table 5-10 Result comparison table of DMUs

DMU	Capital Cost (TL)	Total Cost (TL)	DEA Efficiency Scores	Overall Scores
HPS1	78796.8	103625.368	0.854	-
HPS2	68486.4	98326.191	1	0.4925
HPS3	47174.4	72002.968	0.952	-
HPS4	42282	72121.791	1	0.5046
LED1	89954.52	93706.686	1	0.6993
LED2	89954.52	95149.407	1	0.6388
LED3	102897	106650.84	1	0.6828
LED4	110136.78	115582.575	1	0.6369

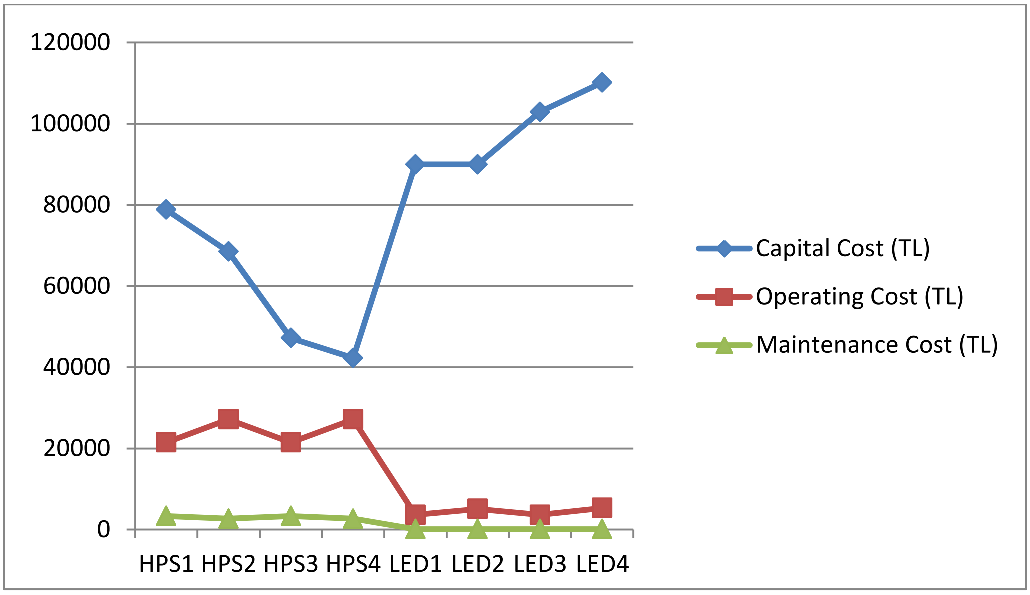

Figure 5-26 The cost diagram of DMUs

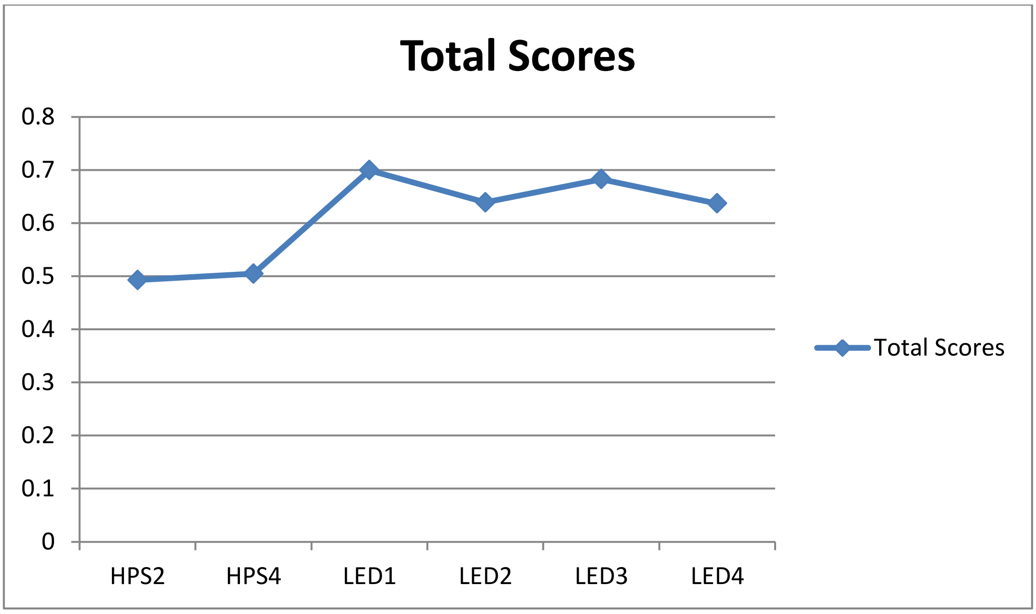

Figure 5-27 The total scores of DMUs

6 CONCLUSION

6.1 Summary

The motivation of this thesis is to support critical decision process on roadway lighting alternative selection under multiple criteria decision making. The market share of the sector is remarkable enough. As mentioned before the street outdoor lighting takes a share of 4.73% of the overall tertiary sector electricity consumption according to Energy Efficiency Status Report of European Commission (2012) and the percentage of general lighting, which road lighting is weighted in it, is 2% in Turkey according to The Annual Energy Report of Turkey (2013). As a consequence, the market for replacement or renovation of roadway lighting installations is sufficiently large to attract road keepers' attention to optimize the cost and energy.

This thesis is an originally structured multi-methodological approach based on the systematic application of Data Envelopment Analysis (DEA), Quality Function Deployment (QFD) and Simple Additive Weighting (SAW) methods which has three main parts.

The first section contains technical information and the literature survey for roadway lighting, data envelopment analysis, quality function deployment and simple additive weighting. Even there are limitless studies on roadway lighting, we could not find any analysis or study on roadway lighting selection by using DEA, QFD and SAW.

Second section explains the originally established multi-methodological approach based on the DEA, QFD and SAW to select the best roadway lighting alternative. This multi-methodological approach is a well-defined analytical method for roadway lighting selection however this originally established method can be applied to the other areas, sectors and industries as a decision making tool.

Final section consists of case study. HPS and LED technologies were analyzed in order to select efficient and sufficient roadway lighting alternative. This analysis consists of both quantitative and qualitative methods. The important part of this case study was the answering the voice of customer beside the cost assessment. The voice of customer is an essential parameter for every type of service management in order to satisfy the consumer expectations. This integrated approach also responds to the environmental factors for a case study of a green university campus.

6.2 Contributions and Main Findings

The main finding of this thesis is the DEA, QFD and SAW integrated multi-methodological decision making tool itself. The DEA analyze the efficiency of the alternatives. The QFD responds to voice of customer and meet the customer requirements with the technical attributes of alternatives. The SAW normalize all the values and weight them to rank for the best option. The primary intent to establish an originally structured integrated multi-methodological decision making approach was to support this thesis. This proposed approach was highly useful and gave the right direction for roadway lighting selection problem. While this proposed approach is implemented particularly for selecting roadway lighting, it can be useful for all types of selection problems.

The earlier studies were mostly about the cost assessment or technical analysis. The strengths of this study were the integration of those cost and technical analysis with the customer expectations. Because beside the cost efficiency, the energy efficiency is vital for environment, the lighting sufficiency is important for road safety, the aesthetic design is significant for the texture of the city or campus.

All results were verified in DIALux. This was approval of our multi-methodological approach. When examined the results in Chapter 5 it can be seen that capital cost as initial purchase cost should not be the main criteria for a selection problem. Efficiency, technical quality and satisfaction of the customer expectations are as important as costs.

The DEA results showed the efficient roadway lighting selection as six from the eight. The alternative LED3 had the best score after the QFD weights implemented in terms of SAW. As can be seen from the results of this thesis LED technology is efficient to change old luminaires. But also HPS technology is convenient with approximate scores to LED.

6.3 Future Study

We studied some decision making methods to select efficient roadway lighting with limited selected technical measures. We propose that DEA, QFD and SAW may be advantageous for technology selection. Other decision making methods may be examined for related processes to discover any assistance. The QFD can be replaced by the axiomatic design and the TOPSIS can be used instead of SAW.

The more advanced and detailed technical analysis with this proposed approach can be constructive to select the better alternatives. Furthermore this thesis can be a beginning or start point to investigate on environmental factors of roadway lighting without the ignorance of the costs.

The renewable energy is new crucial topic and can be apply to roadway lighting Adaptive roadway lighting technologies are the contemporary and also remarkable to analyze. The proposed approach can be implemented to adaptive roadway lighting selection.

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APPENDIX A

Araç yolu 3 (ME4a) / Table

Horizontal illuminance [lx]

13.300	59	46	35	28	25	25	28	35	46	59
11.900	73	71	56	41	40	40	41	56	71	73
10.500	83	88	73	52	50	50	52	73	88	83
9.100	91	90	71	56	55	55	56	71	90	91
7.700	100	91	67	57	57	57	57	67	91	100
m	1.400	4.200	7.000	9.800	12.600	15.400	18.200	21.000	23.800	26.600

Grid: 10 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
62	25	100	0.403	0.251

Figure 0-1 Horizontal illuminance results of HPS1 in DIALux

Luminance with dry roadway [cd/m²]

13.417	2.58	2.72	3.02	3.23	3.38	3.36	3.15	2.89	2.69	2.69
12.250	3.54	4.00	4.26	4.45	4.66	4.82	4.30	4.15	3.82	3.38
11.083	3.65	4.19	4.48	4.52	4.81	5.02	4.45	4.86	4.40	3.48
9.917	3.42	3.88	3.83	3.80	4.31	4.38	4.00	4.33	4.00	3.33
8.750	3.38	3.52	3.41	3.54	3.80	3.83	3.58	3.58	3.61	3.36
7.583	3.52	3.40	3.25	3.42	3.63	3.61	3.27	3.13	3.49	3.50
m	1.400	4.200	7.000	9.800	12.600	15.400	18.200	21.000	23.800	26.600

Grid: 10 x 6 Points

Luminance with new lamp [cd/m²]

13.417	3.86	4.07	4.51	4.83	5.04	5.02	4.70	4.31	4.02	4.01
12.250	5.29	5.97	6.36	6.64	6.96	7.20	6.42	6.20	5.70	5.04
11.083	5.45	6.25	6.69	6.74	7.18	7.50	6.63	7.26	6.57	5.19
9.917	5.10	5.79	5.71	5.67	6.43	6.54	5.97	6.47	5.97	4.97
8.750	5.05	5.26	5.08	5.29	5.67	5.72	5.34	5.34	5.39	5.02
7.583	5.26	5.08	4.85	5.10	5.42	5.39	4.88	4.67	5.21	5.22
m	1.400	4.200	7.000	9.800	12.600	15.400	18.200	21.000	23.800	26.600

Grid: 10 x 6 Points

Figure 0-2 Luminace results for road surface of HPS1 in DIALux

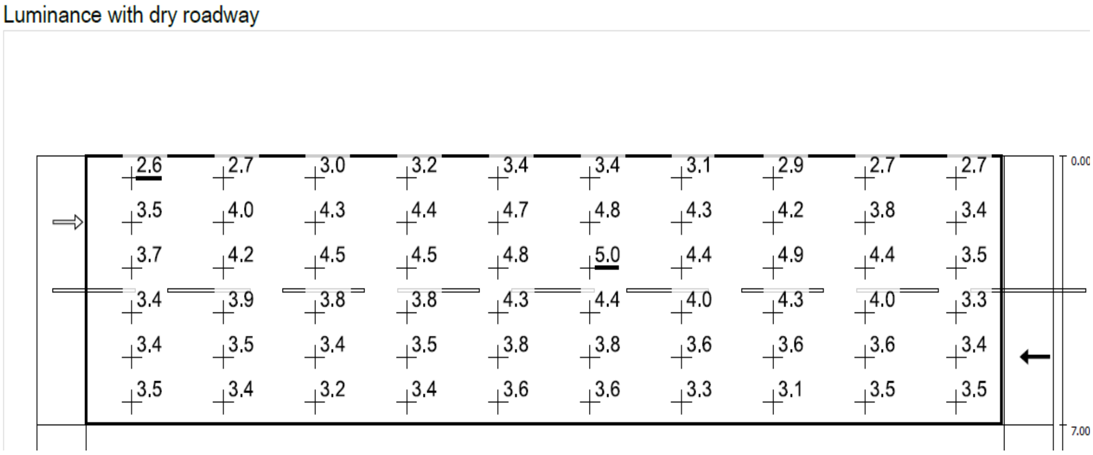


Figure 0-3 Luminace value chart of HPS1 in DIALux

Horizontal illuminance [lx]

6.300	182	162	104	79	68	62	68	79	104	162	182
4.900	155	151	105	78	67	61	67	78	105	151	155
3.500	140	147	105	74	64	59	64	74	105	147	140
2.100	130	132	97	67	57	53	57	67	97	132	130
0.700	113	100	67	50	44	41	44	50	67	100	112
m	1.455	4.364	7.273	10.182	13.091	16.000	18.909	21.818	24.727	27.636	30.545

Grid: 11 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
97	41	182	0.426	0.228

Figure 0-4 Horizontal illuminance results of HPS2 in DIALux

Luminance with dry roadway [cd/m²]

6.417	5.80	5.27	4.17	3.99	4.40	4.46	4.87	4.78	4.77	5.82	5.78
5.250	5.07	5.03	4.07	3.90	4.39	4.59	4.98	5.02	5.06	5.72	5.12
4.083	4.62	4.97	4.20	4.13	4.76	5.14	5.59	5.64	5.91	6.03	4.85
2.917	4.60	5.14	4.69	4.64	5.45	6.14	6.84	6.49	6.78	6.75	4.82
1.750	4.82	5.31	5.12	5.58	6.86	7.66	7.83	7.25	6.91	6.48	4.92
0.583	4.54	4.79	4.76	5.42	6.62	7.12	7.25	6.50	5.76	5.43	4.60
m	1.455	4.364	7.273	10.182	13.091	16.000	18.909	21.818	24.727	27.636	30.545

Grid: 11 x 6 Points

Luminance with new lamp [cd/m²]

6.417	8.66	7.87	6.22	5.95	6.56	6.66	7.27	7.14	7.12	8.69	8.63
5.250	7.56	7.51	6.08	5.82	6.56	6.84	7.43	7.50	7.55	8.54	7.64
4.083	6.89	7.42	6.27	6.16	7.10	7.67	8.35	8.42	8.81	9.00	7.24
2.917	6.87	7.67	7.01	6.92	8.14	9.16	10	9.69	10	10	7.20
1.750	7.19	7.92	7.64	8.33	10	11	12	11	10	9.68	7.34
0.583	6.77	7.15	7.10	8.09	9.88	11	11	9.71	8.60	8.10	6.87
m	1.455	4.364	7.273	10.182	13.091	16.000	18.909	21.818	24.727	27.636	30.545

Grid: 11 x 6 Points

Figure 0-5 Luminace results for road surface of HPS2 in DIALux

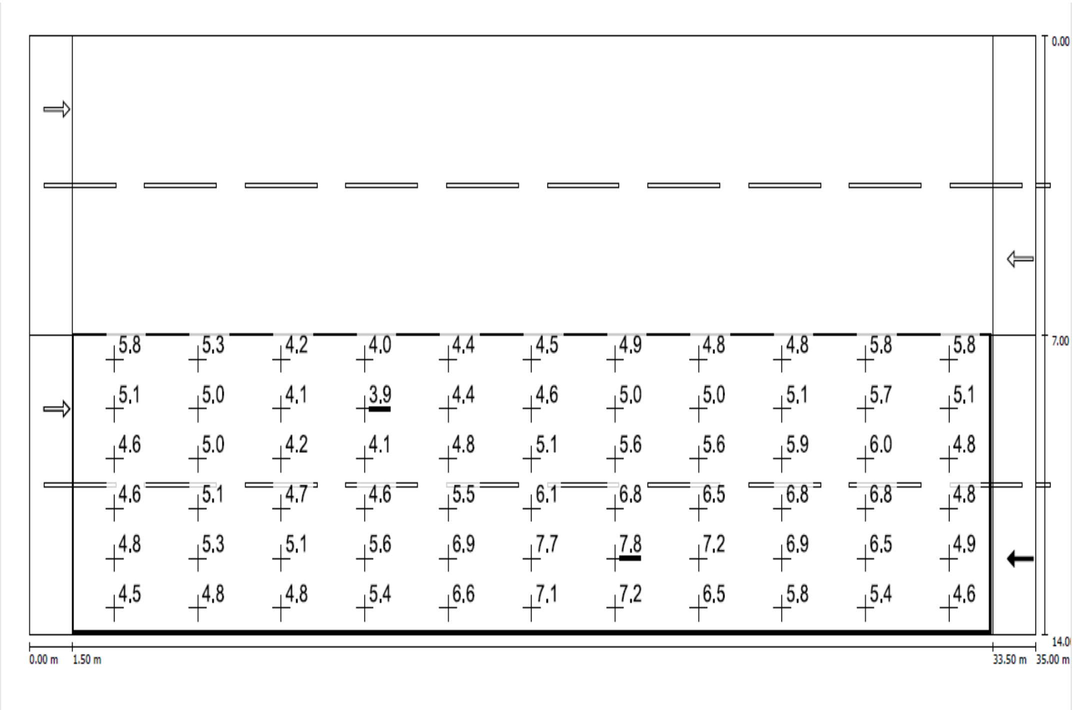


Figure 0-6 Luminace value chart of HPS2 in DIALux

Horizontal illuminance [lx]

6.300	39	33	29	26	26	26	26	29	33	39
4.900	48	41	37	30	28	28	30	37	41	48
3.500	62	53	46	33	29	29	33	46	53	62
2.100	70	59	49	34	29	29	34	49	59	70
0.700	69	56	46	33	27	28	33	46	56	69
m	1.400	4.200	7.000	9.800	12.600	15.400	18.200	21.000	23.800	26.600

Grid: 10 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
41	26	70	0.619	0.365

Figure 0-7 Horizontal illuminance results of HPS3 in DIALux

Luminance with dry roadway [cd/m²]

6.417	1.32	1.26	1.39	1.54	1.58	1.62	1.40	1.28	1.21	1.28
5.250	1.49	1.44	1.56	1.67	1.71	1.80	1.67	1.63	1.48	1.49
4.083	1.85	1.79	1.93	1.98	2.06	2.22	2.14	2.31	1.98	1.92
2.917	2.28	2.26	2.43	2.48	2.63	2.93	2.71	2.96	2.60	2.33
1.750	2.72	2.86	3.24	3.43	3.53	3.61	3.52	3.55	2.98	2.72
0.583	2.96	3.24	3.71	3.92	3.97	4.01	3.91	3.74	3.00	2.82
m	1.400	4.200	7.000	9.800	12.600	15.400	18.200	21.000	23.800	26.600

Grid: 10 x 6 Points

Luminance with new lamp [cd/m²]

6.417	1.96	1.87	2.08	2.30	2.37	2.42	2.09	1.91	1.81	1.91
5.250	2.23	2.14	2.33	2.50	2.55	2.69	2.50	2.44	2.22	2.22
4.083	2.76	2.67	2.88	2.95	3.08	3.32	3.20	3.45	2.96	2.86
2.917	3.40	3.38	3.62	3.70	3.93	4.38	4.05	4.42	3.88	3.48
1.750	4.06	4.27	4.84	5.12	5.28	5.38	5.25	5.29	4.45	4.07
0.583	4.42	4.83	5.54	5.86	5.93	5.99	5.84	5.59	4.48	4.21
m	1.400	4.200	7.000	9.800	12.600	15.400	18.200	21.000	23.800	26.600

Grid: 10 x 6 Points

Figure 0-8 Luminace results for road surface of HPS3 in DIALux

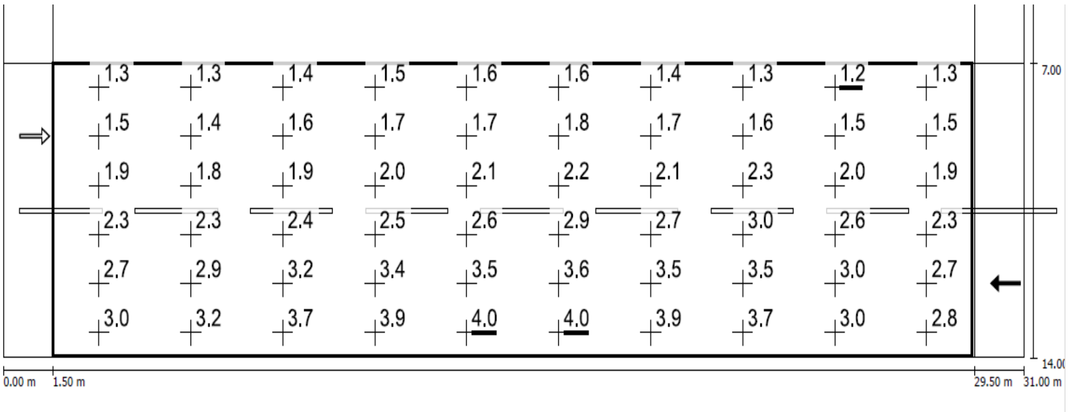


Figure 0-9 Luminace value chart of HPS3 in DIALux

Horizontal illuminance [lx]

13.300	115	97	68	45	32	27	28	32	45	68	97	115
11.900	121	104	76	50	35	31	31	35	50	76	104	121
10.500	117	97	74	51	37	34	34	37	51	74	97	117
9.100	106	93	71	52	38	35	35	38	52	71	93	106
7.700	100	92	71	53	40	35	35	40	53	71	92	100
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
67	27	121	0.412	0.226

Figure 0-10 Horizontal illuminance results of HPS4 in DIALux

Luminance with dry roadway [cd/m²]

13.417	3.57	3.59	3.47	3.95	4.61	5.25	5.40	5.53	5.90	5.78	4.98	3.99
12.250	4.04	4.10	4.01	4.35	4.89	5.59	5.55	5.49	6.05	6.04	5.15	4.25
11.083	3.86	3.70	3.46	3.54	3.76	4.41	4.54	4.48	4.81	4.99	4.75	4.01
9.917	3.41	3.19	2.92	2.89	2.86	3.24	3.62	3.61	4.06	4.22	3.89	3.63
8.750	3.15	3.01	2.69	2.53	2.48	2.83	3.07	3.06	3.51	3.52	3.39	3.25
7.583	3.01	2.89	2.67	2.49	2.35	2.65	2.88	2.95	3.21	3.22	3.21	3.06
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Luminance with new lamp [cd/m²]

13.417	5.33	5.35	5.18	5.89	6.88	7.84	8.06	8.25	8.81	8.63	7.44	5.96
12.250	6.04	6.12	5.99	6.50	7.30	8.35	8.28	8.20	9.03	9.02	7.69	6.34
11.083	5.76	5.52	5.17	5.28	5.61	6.58	6.77	6.69	7.18	7.44	7.09	5.98
9.917	5.08	4.76	4.35	4.31	4.27	4.84	5.41	5.39	6.06	6.30	5.80	5.42
8.750	4.70	4.49	4.01	3.78	3.69	4.22	4.58	4.57	5.24	5.26	5.06	4.85
7.583	4.50	4.31	3.99	3.71	3.51	3.96	4.29	4.40	4.79	4.80	4.79	4.56
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Figure 0-11 Luminace results for road surface of HPS4 in DIALux

Luminance with dry roadway

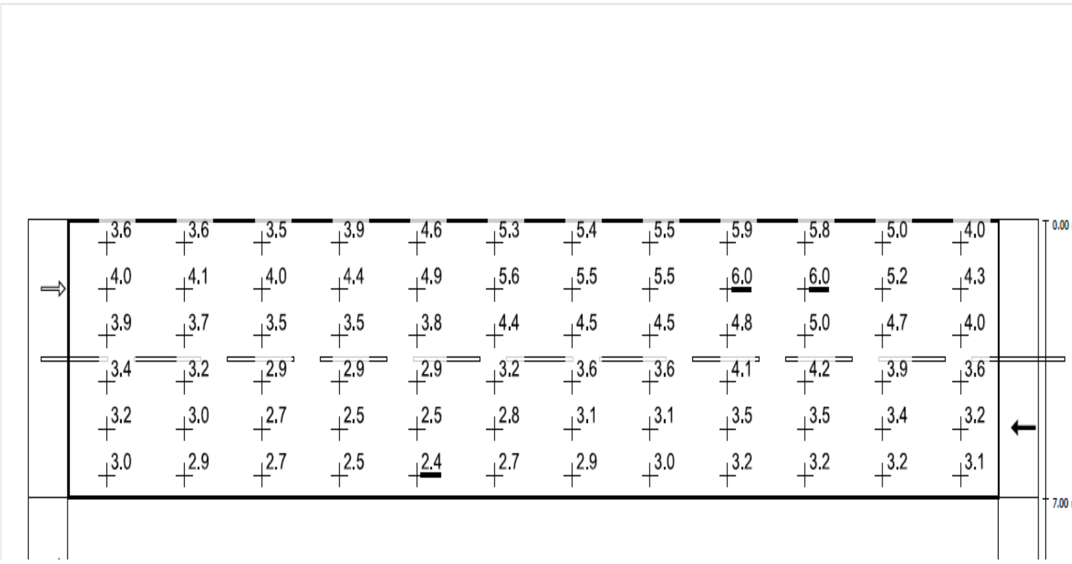


Figure 0-12 Luminace value chart of HPS4 in DIALux

Horizontal illuminance [lx]

13.300	20	16	11	7.93	6.15	5.43	5.43	6.17	7.93	11	16	20
11.900	18	15	11	8.65	7.11	6.37	6.37	7.11	8.66	11	15	18
10.500	18	15	12	9.82	8.56	7.85	7.85	8.56	9.82	12	15	18
9.100	17	15	13	11	9.93	9.65	9.65	9.94	11	13	15	17
7.700	16	15	14	12	11	11	11	11	12	14	15	16
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
12	5.43	20	0.454	0.276

Figure 0-13 Horizontal illuminance results of LED1 in DIALux

Luminance with dry roadway [cd/m²]

13.417	0.65	0.68	0.79	0.97	1.12	1.18	1.19	1.14	1.08	0.98	0.83	0.72
12.250	0.72	0.80	0.94	1.15	1.28	1.32	1.26	1.18	1.09	0.92	0.80	0.71
11.083	0.68	0.73	0.80	0.93	1.05	1.12	1.07	1.05	0.91	0.80	0.75	0.66
9.917	0.61	0.62	0.65	0.75	0.82	0.88	0.93	0.90	0.84	0.76	0.68	0.62
8.750	0.57	0.57	0.58	0.65	0.74	0.84	0.86	0.81	0.77	0.65	0.59	0.57
7.583	0.55	0.56	0.60	0.65	0.72	0.81	0.84	0.82	0.75	0.64	0.57	0.55
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Luminance with new lamp [cd/m²]

13.417	0.98	1.02	1.18	1.45	1.68	1.76	1.77	1.70	1.61	1.46	1.24	1.08
12.250	1.08	1.19	1.40	1.71	1.91	1.96	1.89	1.76	1.62	1.37	1.19	1.07
11.083	1.02	1.09	1.19	1.38	1.57	1.67	1.59	1.57	1.36	1.19	1.12	0.99
9.917	0.91	0.93	0.97	1.12	1.23	1.32	1.39	1.35	1.26	1.13	1.01	0.93
8.750	0.86	0.86	0.86	0.97	1.10	1.25	1.28	1.21	1.15	0.97	0.88	0.86
7.583	0.83	0.83	0.89	0.97	1.08	1.22	1.25	1.23	1.12	0.95	0.84	0.82
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Figure 0-14 Luminace results for road surface of LED1 in DIALux

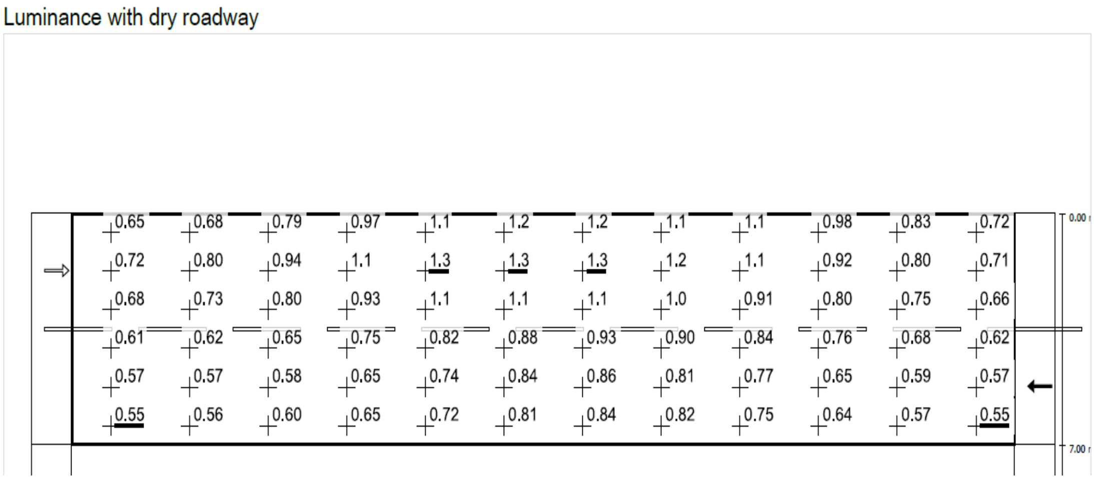


Figure 0-15 Luminace value chart of LED1 in DIALux

Horizontal illuminance [lx]

13.300	26	20	15	10	8.05	7.10	7.10	8.07	10	15	20	26
11.900	24	20	15	11	9.30	8.33	8.33	9.30	11	15	20	24
10.500	23	20	16	13	11	10	10	11	13	16	20	23
9.100	22	20	16	14	13	13	13	13	14	16	20	22
7.700	21	20	18	16	15	14	14	15	16	18	20	21
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
16	7.10	26	0.454	0.276

Figure 0-16 Horizontal illuminance results of LED2 in DIALux

Luminance with dry roadway [cd/m²]

13.417	0.86	0.89	1.03	1.27	1.47	1.54	1.55	1.49	1.41	1.28	1.09	0.95
12.250	0.94	1.05	1.23	1.50	1.67	1.72	1.65	1.54	1.42	1.20	1.04	0.93
11.083	0.90	0.95	1.04	1.21	1.38	1.46	1.39	1.37	1.19	1.05	0.98	0.87
9.917	0.80	0.81	0.85	0.98	1.08	1.16	1.22	1.18	1.10	0.99	0.89	0.81
8.750	0.75	0.75	0.76	0.85	0.97	1.10	1.12	1.06	1.01	0.85	0.77	0.75
7.583	0.72	0.73	0.78	0.85	0.95	1.07	1.10	1.07	0.98	0.83	0.74	0.71
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Luminance with new lamp [cd/m²]

13.417	1.28	1.33	1.54	1.90	2.19	2.30	2.32	2.23	2.10	1.91	1.62	1.41
12.250	1.41	1.56	1.83	2.24	2.50	2.57	2.47	2.30	2.12	1.80	1.55	1.39
11.083	1.34	1.42	1.56	1.81	2.06	2.19	2.08	2.05	1.77	1.56	1.47	1.29
9.917	1.19	1.21	1.27	1.46	1.61	1.73	1.82	1.77	1.65	1.48	1.32	1.21
8.750	1.12	1.12	1.13	1.27	1.44	1.64	1.67	1.58	1.51	1.27	1.16	1.12
7.583	1.08	1.09	1.16	1.27	1.41	1.59	1.64	1.60	1.46	1.24	1.10	1.07
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Figure 0-17 Luminace results for road surface of LED2 in DIALux

Luminance with dry roadway

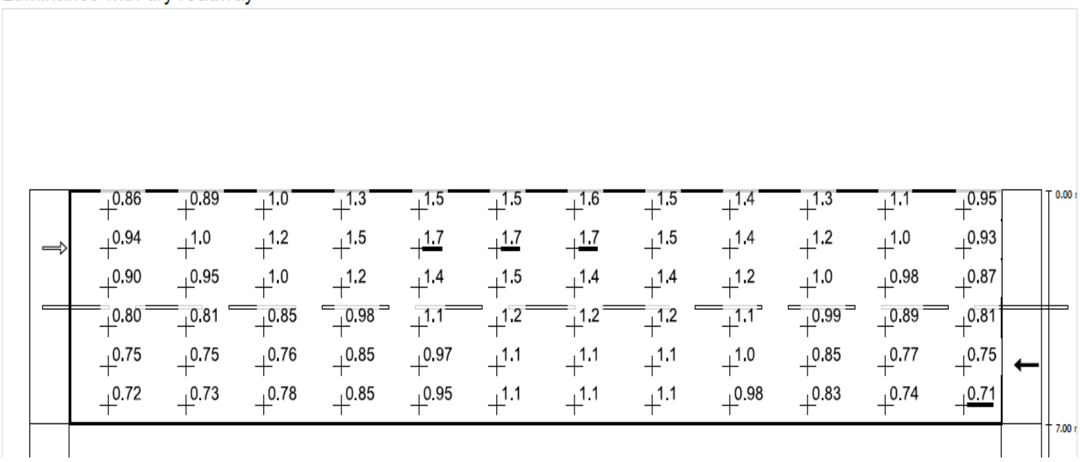


Figure 0-18 Luminace value chart of LED2 in DIALux

Horizontal illuminance [lx]

13.300	22	17	12	7.94	6.07	5.57	6.08	7.95	12	17	22
11.900	20	16	12	8.47	6.60	6.10	6.60	8.47	12	16	20
10.500	19	15	13	9.19	7.67	7.08	7.67	9.20	13	15	19
9.100	18	15	13	10	9.32	8.94	9.32	10	13	15	18
7.700	17	16	14	12	11	10	11	12	14	16	17
m	1.500	4.500	7.500	10.500	13.500	16.500	19.500	22.500	25.500	28.500	31.500

Grid: 11 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
13	5.57	22	0.444	0.251

Figure 0-19 Horizontal illuminance results of LED3 in DIALux

Luminance with dry roadway [cd/m²]

13.417	0.73	0.73	0.81	0.97	1.08	1.13	1.13	1.12	1.06	0.93	0.82
12.250	0.77	0.81	0.94	1.10	1.17	1.18	1.13	1.12	0.99	0.86	0.78
11.083	0.70	0.70	0.80	0.89	0.97	0.92	0.94	0.90	0.87	0.77	0.69
9.917	0.61	0.62	0.67	0.72	0.75	0.81	0.82	0.83	0.80	0.69	0.64
8.750	0.59	0.57	0.57	0.63	0.72	0.76	0.76	0.76	0.67	0.60	0.59
7.583	0.58	0.56	0.59	0.65	0.73	0.78	0.80	0.76	0.66	0.59	0.57
m	1.500	4.500	7.500	10.500	13.500	16.500	19.500	22.500	25.500	28.500	31.500

Grid: 11 x 6 Points

Luminance with new lamp [cd/m²]

13.417	1.09	1.08	1.21	1.45	1.61	1.69	1.69	1.67	1.58	1.38	1.22
12.250	1.15	1.21	1.40	1.65	1.75	1.76	1.68	1.67	1.48	1.28	1.16
11.083	1.04	1.04	1.20	1.33	1.45	1.37	1.41	1.34	1.31	1.16	1.03
9.917	0.92	0.93	1.00	1.07	1.13	1.22	1.22	1.23	1.20	1.02	0.95
8.750	0.87	0.85	0.86	0.94	1.07	1.13	1.13	1.13	1.00	0.90	0.88
7.583	0.86	0.84	0.88	0.97	1.08	1.16	1.19	1.13	0.98	0.88	0.85
m	1.500	4.500	7.500	10.500	13.500	16.500	19.500	22.500	25.500	28.500	31.500

Grid: 11 x 6 Points

Figure 0-20 Luminace results for road surface of LED3 in DIALux

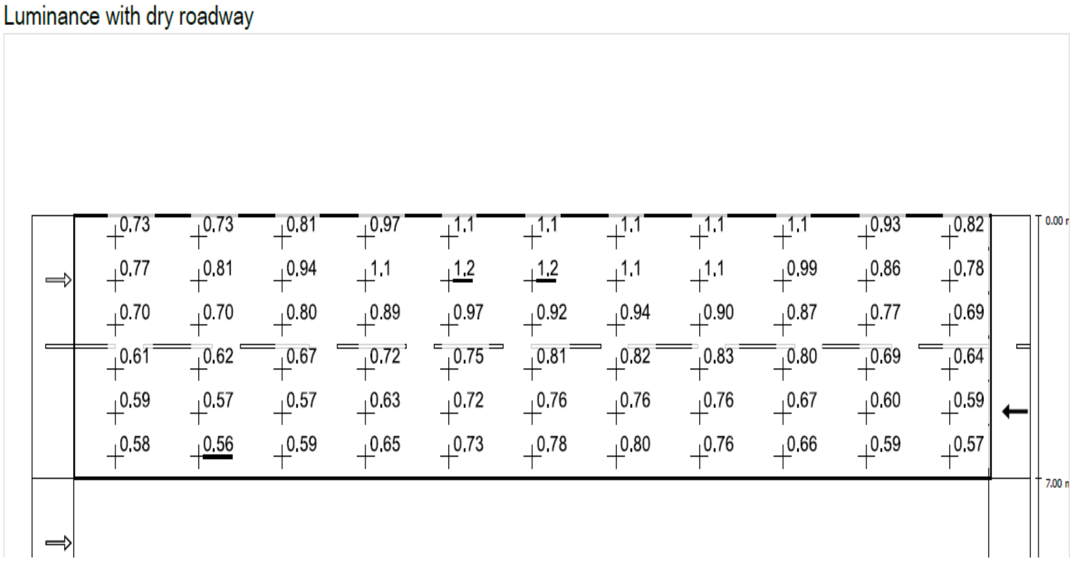


Figure 0-21 Luminace value chart of LED3 in DIALux

Horizontal illuminance [lx]

13.300	32	25	17	12	8.45	7.27	7.28	8.46	12	17	25	32
11.900	29	23	17	12	9.22	8.00	8.00	9.22	12	17	23	29
10.500	27	22	18	13	11	9.39	9.39	11	13	18	22	27
9.100	26	22	18	15	13	12	12	13	15	18	22	26
7.700	25	23	20	17	15	13	13	15	17	20	23	25
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 5 Points

EAvg [lx]	EMin [lx]	EMax [lx]	g1	g2
17	7.27	32	0.420	0.224

Figure 0-22 Horizontal illuminance results of LED4 in DIALux

Luminance with dry roadway [cd/m²]

13.417	1.00	0.92	0.93	1.18	1.42	1.57	1.63	1.62	1.62	1.51	1.32	1.15
12.250	1.02	1.00	1.08	1.38	1.58	1.68	1.66	1.60	1.61	1.39	1.21	1.09
11.083	0.94	0.89	0.97	1.12	1.30	1.37	1.31	1.35	1.27	1.22	1.09	0.97
9.917	0.85	0.81	0.84	0.91	1.00	1.07	1.15	1.15	1.14	1.14	0.97	0.90
8.750	0.81	0.78	0.75	0.81	0.89	1.03	1.07	1.06	1.06	0.93	0.85	0.83
7.583	0.81	0.77	0.80	0.84	0.90	1.00	1.07	1.12	1.06	0.92	0.83	0.81
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Luminance with new lamp [cd/m²]

13.417	1.49	1.37	1.39	1.77	2.12	2.34	2.44	2.42	2.42	2.25	1.97	1.72
12.250	1.53	1.49	1.62	2.06	2.36	2.51	2.48	2.39	2.40	2.07	1.81	1.62
11.083	1.40	1.33	1.44	1.67	1.94	2.05	1.95	2.01	1.90	1.82	1.63	1.44
9.917	1.27	1.21	1.26	1.36	1.49	1.60	1.72	1.72	1.70	1.69	1.45	1.34
8.750	1.22	1.16	1.12	1.20	1.33	1.53	1.59	1.58	1.58	1.40	1.27	1.24
7.583	1.20	1.16	1.20	1.25	1.34	1.50	1.60	1.67	1.58	1.38	1.24	1.21
m	1.458	4.375	7.292	10.208	13.125	16.042	18.958	21.875	24.792	27.708	30.625	33.542

Grid: 12 x 6 Points

Figure 0-23 Luminace results for road surface of LED4 in DIALux

Luminance with dry roadway

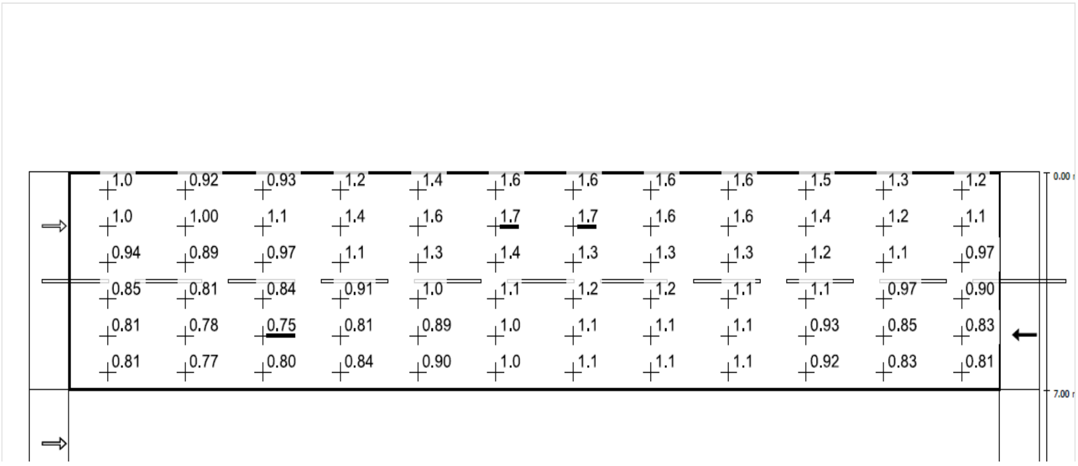


Figure 0-24 Luminance value chart of LED4 in DIALux

APPENDIX B

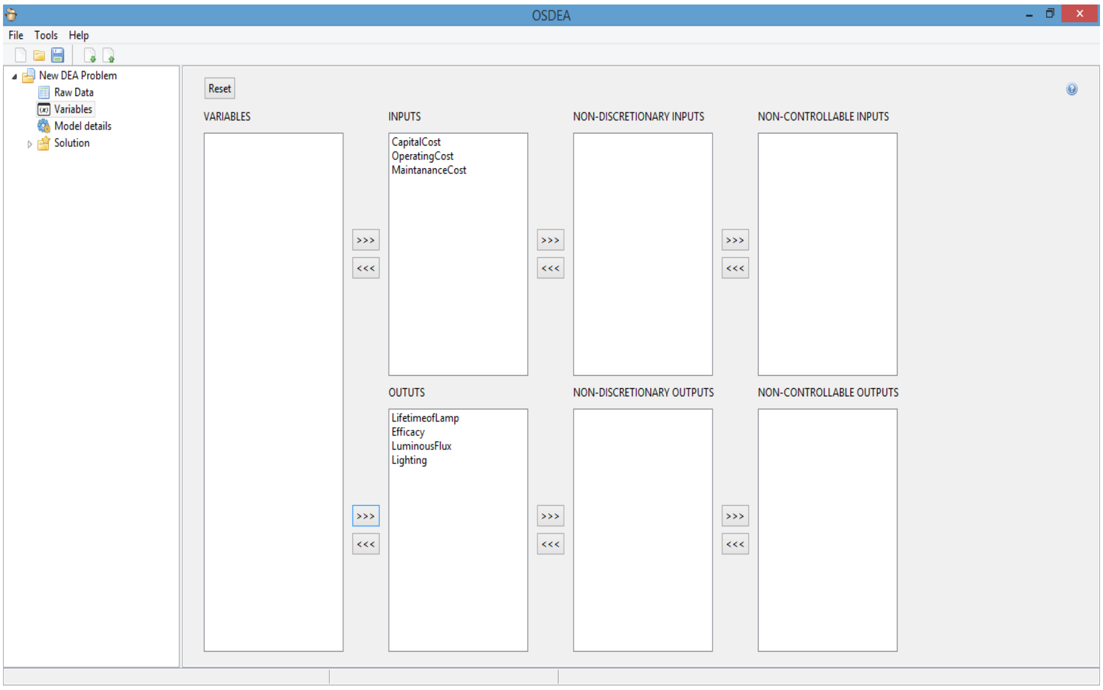


Figure 0-1 Variable selection interface in OSDEAGUI

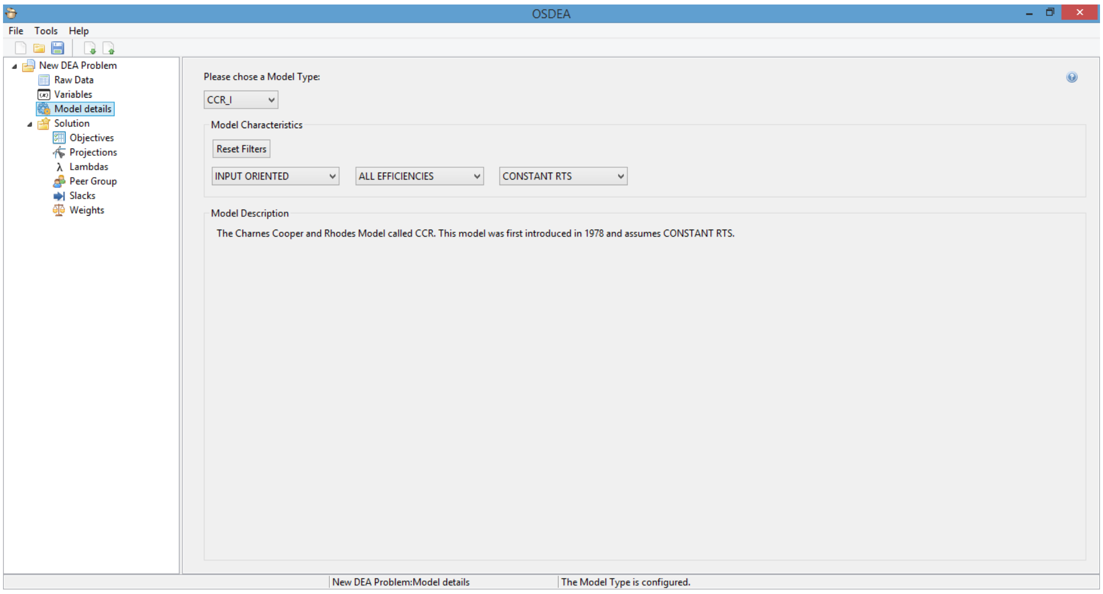
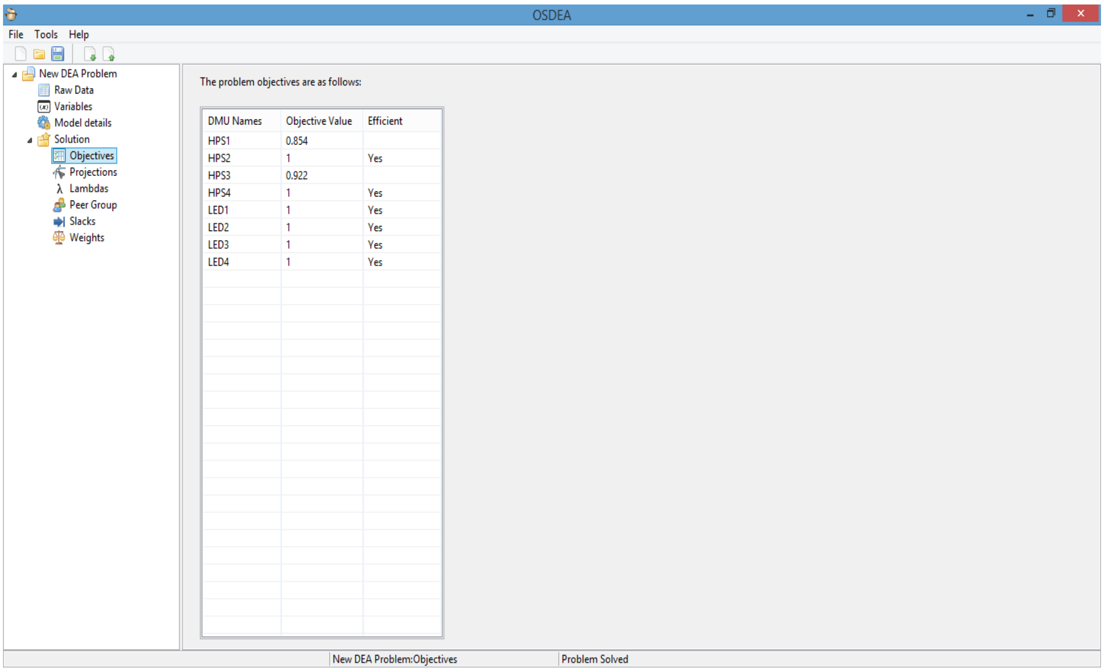
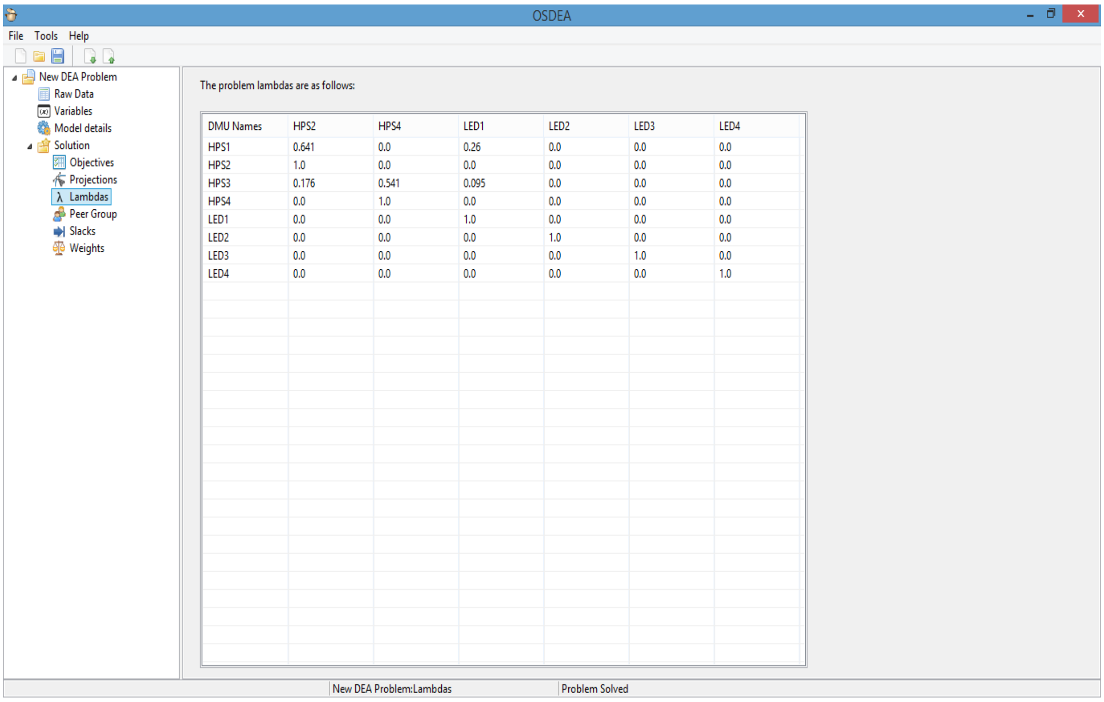


Figure 0-2 Model details interface in OSDEAGUI



DMU Names	Objective Value	Efficient
HPS1	0.854	
HPS2	1	Yes
HPS3	0.922	
HPS4	1	Yes
LED1	1	Yes
LED2	1	Yes
LED3	1	Yes
LED4	1	Yes

Figure 0-3 Objectives (Resulsts) interface in OSDEAGUI



DMU Names	HPS2	HPS4	LED1	LED2	LED3	LED4
HPS1	0.641	0.0	0.26	0.0	0.0	0.0
HPS2	1.0	0.0	0.0	0.0	0.0	0.0
HPS3	0.176	0.541	0.095	0.0	0.0	0.0
HPS4	0.0	1.0	0.0	0.0	0.0	0.0
LED1	0.0	0.0	1.0	0.0	0.0	0.0
LED2	0.0	0.0	0.0	1.0	0.0	0.0
LED3	0.0	0.0	0.0	0.0	1.0	0.0
LED4	0.0	0.0	0.0	0.0	0.0	1.0

Figure 0-4 Problem lambdas interface in OSDEAGUI

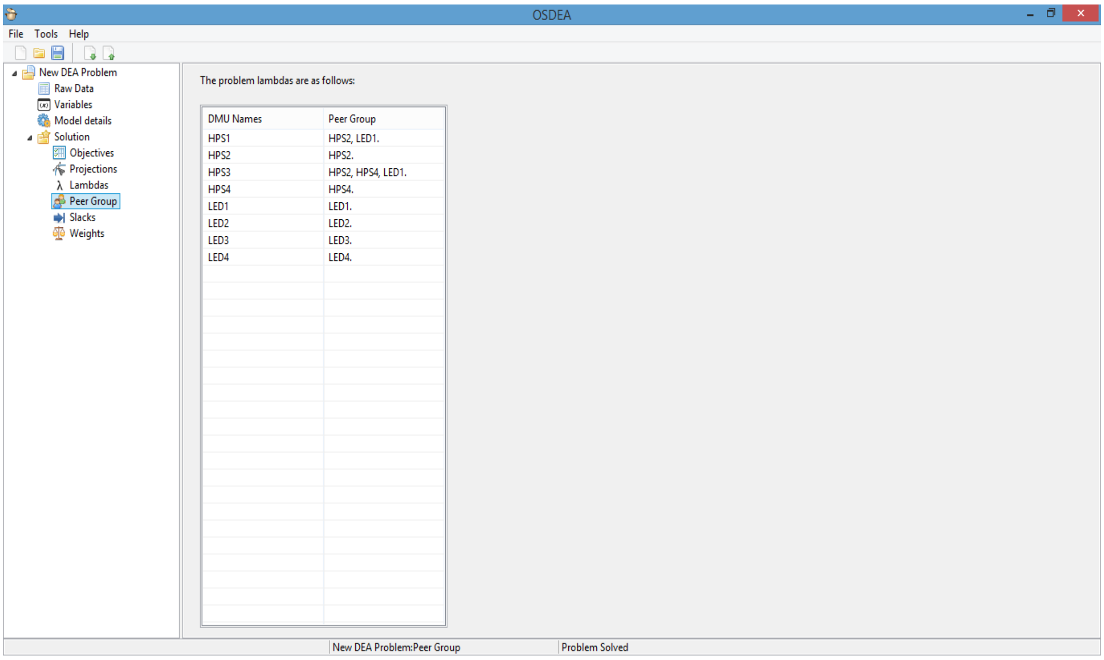


Figure 0-5 Problem lambdas interface in OSDEAGUI