AN OPTIMIZATION MODEL FOR LUMINAIRE LAYOUT DESIGN IN OFFICE SPACES: OptimLUM

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ABSTRACT

AN OPTIMIZATION MODEL FOR LUMINAIRE LAYOUT DESIGN IN OFFICE SPACES: OptimLUM

There are several methods used in lighting design. The realistic methods have been developed by the computer graphics which use the engineering computational tools and architectural rendering together. Although lighting designers would design an accurate lighting system which provides desired illuminance levels through computer graphics, it is still necessary to propose optimal and alternative solutions by maximizing comfort conditions and minimizing energy consumption by practical techniques. Thus, the purpose of this study is to propose an optimization model for offices to estimate the accurate layout, number and type of light sources according to visual comfort conditions and energy efficiency.

Model is conducted mathematically based on the primary objective which is to provide uniform illumination on work plane with the constraints about vertical illuminances and luminance values. Model named OptimLUM is validated by comparing measurements and simulations. Finally, OptimLUM offer some energy efficient layouts for different office sizes with different number and type of light sources. To be more energy efficient and decrease the energy loads by artificial lighting, these layouts were integrated with daylight.

Unlike common lighting design solutions, OptimLUM offers unsymmeterical but more energy efficient layouts by using minimum number of luminaires. According to outputs of the model integrated with daylight, for artificial lighting design in offices, lighting designers should decide on the number and type of luminaires by comparing the darkest and day usage conditions. As a result, by using OptimLUM during the design phase, designers can provide visual comfort conditions for office users while reducing the energy loads of artificial lighting.

ÖZET

OFİS MEKANLARINDA AYDINLATMA AYGITLARININ YERLEŞİM TASARIMI İÇİN BİR OPTİMİZASYON MODELİ: OptimLUM

Aydınlatma tasarımında kullanılan birçok yöntem bulunmaktadır. En yaygın kullanılan ve gerçekçi sonuçlar elde edilebilen bilgisayar yazılımları; mühendislik hesaplama araçları ile mimari üç boyutlu görüntü oluşturma araçlarını bir arada kullanır. Aydınlatma tasarımcıları, bilgisayar yazılımları ile istenilen aydınlık düzeylerini sağlayan doğru aydınlatma sistemleri tasarlayabilmelerine rağmen pratik tekniklerle konfor koşullarını maksimize eden ve enerji verimliliğini en aza indiren optimum ve alternatif çözümler önermelidir. Bu çalışmanın genel amacı, ofislerde ışık kaynaklarının konumunun, sayısının ve türünün en doğru şekliyle tahmin edilebilmesi için bir optimizasyon modeli oluşturmaktır.

Matematiksel olarak kurulan modelin ana amacı; çalışma düzleminde eşit dağılımlı bir aydınlık düzeyi sağlamaktır. Ayrıca dikey yüzeylerde aydınlık düzeyi ve parıltı değerleri ile ilgili kısıtlar ile görsel konfor koşullarını sağlamaktadır. OptimLUM ölçüm ve simülasyon sonuçları ile karşılaştırılarak valide edilmiştir. Son olarak, OptimLUM farklı ofis büyüklükleri için faklı sayıda ve tipte armatürle enerji verimli yerleşim düzenleri sunmuştur. Daha enerji verimli olması ve yapay aydınlatmanın enerji yüklerini azaltmak için gün ışığı ile bütünleştirilmiştir.

OptimLUM genel aydınlatma tasarımlarının aksine simetrik olmayan ancak daha az sayıda armatür ile daha enerji etkim çözümler sunmaktadır. Modelin gün ışığı ile bütünleştirilmiş sonuçlarına göre, tasarımcılar ofislerde yapay aydınlatma tasarımında, en karanlık ve gün boyu kullanım koşullarının karşılaştırarak armatür sayısı ve türüne karar vermelidir. Sonuç olarak tasarımcılar, tasarım aşamasında OptimLUM kullanarak yapay aydınlatma ile harcanan enerjiyi düşürürken, ofis kullanıcıları için görsel konfor koşullarını sağlayabilirler.

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CHAPTER 1

INTRODUCTION

In this chapter are presented first, the initial idea and arguments explained in relation to previous studies who worked on similar subjects. Then, objectives are clarified with research questions that promote the research. After these sections, the benefits and significance of the study and its differentiation from other studies are mentioned. Lastly, lighting terms which are important and will be used during this study are described.

1.1. Argument

Lighting design of a workspace is a complicated task that includes multiple criteria based on many physical and psychological aspects. Occupants spend a large part of their time at workspaces. So, they need to work in comfortable and healthy environments (Bal 2005). Appropriate lighting conserves eye health, increases the work performance, and provides visual comfort (Apaydin 2012). Besides, a properly-designed lighting system helps to balance the lighting, heating and cooling loads by decreasing the energy consumption. Energy consumption of workspaces is taken into consideration because a significant amount of buildings' energy consumption is due to artificial lighting. The planning of artificial lighting systems involves consideration about metrics of lighting quality and quantity (Bal 2005). The basic metric for the quantity of lighting design is illuminance. Illuminance depends on the features of visual tasks, room surfaces, photometric data of the lighting sources (the lamp/and the luminaire) and their location (IESNA 2011). It is necessary to distribute illuminance uniformly in the indoor environment, since non-uniform light distribution causes glare. One metric to determine the uniformity is the light distribution curve of the luminaire which is unique for each of them (CIBSE/SLL 2002). The light distribution curve of the luminaire consists of information about the power of the light source on different angles of x, y and z plane. Illuminance is calculated according to this information. The other metric is the location of luminaires. It is necessary to determine the correct position of the luminaire to avoid unbalanced illuminance distribution while selecting the accurate light source.

Lighting designers select and decide on the types of lamps and luminaires according to these metrics. Simulations are the assisting tools in their decision process. They present many design alternatives. However, they do not have the power to show the most accurate or optimum position of light sources according to candle power distributions (Monjur Mourshed, Shikder, and Price 2011). Simulation tools are helpful in proposing lighting design decisions in general; however, they are not the decision maker to propose the best solution. Potential solutions/designers' assumptions for better performance cannot be confirmed or rejected through effective search mechanism.

Lighting design alternatives may present some bright or dark regions in the horizontal plane due to the overlap or gap of the candle power distribution curve. Non-uniform light distribution results in glare when one region in the interior space is brighter than the general brightness (CIBSE/SLL 2002). Thus, it is necessary to determine the correct position of the lighting fixture. The effective and dynamic search mechanism to find optimum solutions should be integrated in the lighting design process. It is worth to study optimization techniques in this sense.

Although optimization techniques have been widely used in the field of engineering (Ravindran, Ragsdell, and Reklaitis 2006), (Wright and Loosemore 2001), (Magnier and Haghighat 2010) i.e. chemical, industrial, and mechanical engineering etc., they are not a well-known technique in the field of architecture. It is necessary to make a contribution to literature in this sense.

Lighting designers make decisions about the locations of luminaires by estimating illuminance levels through simulations. However, by employing optimization techniques, combinations of different design (layout, lamp and luminaire selection) alternatives would be tested together in one model to obtain the most accurate locations of light sources according to defined comfort and efficiency constraints. Simulation tools instruct the designers with the inclusion of parameters in one model; however, an optimization model provides design decision solutions with the inclusion of multiple design criteria. So, that optimum solution provides the optimal illuminance on the work plane and of the luminous power.

Thus, it is necessary to find the optimal solution for lighting design which may be achieved by maximizing comfort conditions, and minimizing the energy consumption of the lighting scheme.

The main purpose of this study is to estimate the most accurate locations of light sources according to visual comfort conditions and energy efficiency by proposing a new model. The secondary aim is to validate the model by measurements and a simulation tool; DIALux (DIALux, 2014).

1.2. Motivation

Objectives of this study were formulated under the purpose of constructing an optimization model to estimate the most accurate location, number and type of light sources in an office. According to these, first objective of the thesis is to develop a flexible and effective model named OptimLUM for different types of luminaires and room sizes to optimize multi objective problems of lighting design which are to provide visual comfort metrics and energy loads together.

Another objective of the study is to validate this model by simulation program; DIALux and getting measurements in an actual test case. There were some research questions defined; one being the primary and the other being the secondary.

Furthermore, another objective is to integrate OptimLUM with daylight to minimize energy loads of artificial light sources.

The research questions of the study were:

- How are visual comfort parameters calculated?
- Which parameters of visual comfort are effective on luminaire layout?
- How does the mathematical model be flexible for usage of varying luminaire types in different room sizes?
- How can this model (OptimLUM) be evaluated based on its applicability and validity?
- How can this model (OptimLUM) be evaluated based on energy efficiency?
- How can this model (OptimLUM) be integrated with daylight?

1.3. Significance of the Study

Lighting designers deal with a multi-objective problem while proposing a layout of artificial light sources. Optimization techniques have been used widely in the field of engineering but they are new in architectural studies according to literature. Heuristics is one of these optimization techniques that can solve this type of multi-objective problems but they are not widely applied on lighting design (Rabaza et al. 2013). The proposed method of this dissertation is a new and alternative approach of applying a mathematical model with an optimization process in an architectural research; especially in lighting design.

As it is figured out in studies about lighting (Cassol et al. 2011), (Shikder, Mourshed, and Price 2010), (Wright and Mourshed 2009), researchers use optimization techniques for different variables such as proportions of architectural elements, estimating optimum luminous power etc. Several studies (Congradac et al. 2012), (De Carli and De Giuli 2009), (Fernández and Besuievsky 2012) deal with energy efficiency by evaluating both daylighting and artificial lighting. By the way, there will be increase of energy efficiency by using daylight. There are only a few studies(Schneider et al. 2009), (Monjur Mourshed, Shikder, and Price 2011), (Tena and Rudomin 1997), (Rocha et al. 2016) to consider the problem of artificial lighting layouts. In an earlier study (Shikder, Mourshed, and Price 2010) researchers aimed to find optimum positions for two different luminaires in two identified and smaller/limited areas. H. Rocha et al. 2016 propose a computer-automated design tool for exterior lighting design. This tool illustrates the possibility of better uniform illumination and energy efficiency.

Apart from the literature, the proposed optimization model runs for the optimum luminaire positions more than one light sources in one identified and determinate area. Thus, mutual impact of luminaires while calculating the illuminance, luminance and uniformity are integrated in the optimization model. The optimization model in this case performs well not only calculating the illuminance at the work plane but also in locating and determining the luminaire positions. There can be also seen in literature that similar studies about lighting and optimization that they have created complicated, non-dynamic model. The model of this study will be a helpful and practical tool for lighting designer while they decide on the locations of luminaires. This model will also be useful in energy saving decisions of lighting design by locating the minimum number of lamps with the required and uniform illuminance.

1.4. Definition of the Terms

In workspaces, the common activities are reading, writing, using a computer and audio-visual communication, video surveillance etc.(Emre 2012). So, there are three aims of the lighting which provide visibility, obtain good image and provide suitable image according to specific purpose (Sirel 2001). By providing appropriate lighting, occupants can be able to see the tiniest part easily; to perceive surface forms and textures correctly; to see colors accurately; to notice the slightest color separations and; to see for a long time without fatigue. By this way, appropriate lighting conserves eye health, increases the work performance, and provides visual comfort (Apaydin 2012). Therefore, there are some recommendations and standards about visual comfort conditions. They consist of the metrics of office lighting quality. In this section, these lighting terms which are important in this study will be explained.

Luminous Flux (LF):

Luminous flux is a physical quantity and represents the amount of light emitted from a light source and perceived by human eye. As it can be understood from this description that luminous flux depends on the power of light source and human eye. The luminous flux's symbol is Φ and its unit is lumen (lm) (The National Framework for Energy Efficiency (Australia) 2009).

Luminous Intensity:

Luminous intensity is the emitted flux from a light source in a given direction. It is used to measure the distribution of light from a luminaire. Symbol of intensity is I and is measured in candelas (cd).

Luminance:

Luminance is the intensity of light emitted from a unit area of a surface in a certain direction. It depends on reflectance factor of surfaces. Reflectance factor (ρ) is calculated based on ratio of luminous flux reflected from a surface to the luminous flux incident on the surface. Symbol of luminance is L and is measured in candelas per square meter (cd/m^2).

It is calculated by the given formulae above;

$$L = \frac{E \times \rho}{\pi} \quad (1.1)$$

E: Illuminance on surface

ρ: Reflectance of surface

***Candle power distribution**:*

Distribution of light output information which is the photometric data of light sources gets from candle power distribution graphs. These distribution curves consist information about power of light source on different angles of horizontal and vertical planes. There are many different artificial light sources on the market. Each different light source has different candle power distribution (Figure 1.1). It can be easily understood from these graphs that luminous flux spreads upwards or downwards, symmetric or asymmetric.

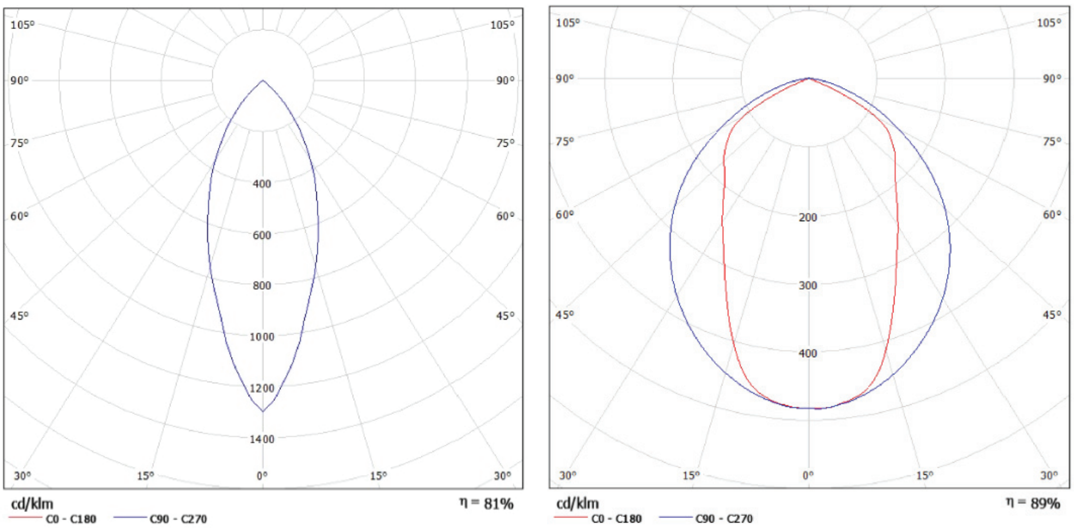

Figure 1.1. Candle power distributions of two different light source

Illuminance of the point or all space is calculated according to candle power distribution charts. These charts comprise numerical photometric data about luminaires via C angle and Gamma angles. C angle is the resulting angle between light source and calculation point on horizontal plane. Gamma angle is the resulting angle between light source and calculation point on vertical plane (Figure 1.2).

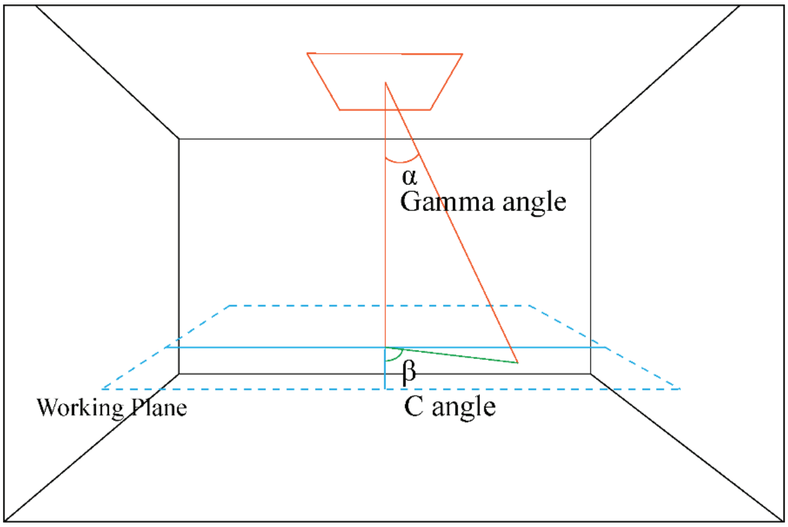

Figure 1.2. C and Gamma angles.

Illuminance:

Illuminance which is the most important lighting design metric affects directly human comfort, psychology and working ability. It can be described as total luminous flux per area (lux). The symbol for illuminance is E. The selection of target illuminance is depended on the features of visual tasks, adaptation between spaces, the occupant's age, and room surfaces. 300 – 500 lx are generally the most appropriate for offices. 500 lux is advised for reading tasks for users between 25 and 65 years old (IESNA 2011). The general lighting can be at a lower level if there is also local lighting (IESNA. Office Lighting Committee 2004).

Uniformity (U):

Uniformity helps to understand differentiation of illuminance levels all spaces. Because different lighting design alternatives proposed may cause some bright or darks regions in the horizontal plane due to the overlap or gap of the candle power distribution curve. Non-uniform light distribution could cause glare when one region in the interior space is brighter than the general brightness (CIBSE/SLL 2002). It is generally defined as ratio of the minimum to the average illuminance. Yet, this ratio is an overall measure to give an idea about illuminance balance. To test illuminance fluctuations in detail, mean relative deviation (MRD) (6) was used calculating relative deviation of illuminance at each point from the average illuminance of the whole space, as cited in literature (Ferentinos and Albright 2005), (Congradac et al. 2012).

Luminous efficacy:

Luminous efficacy is the proportion of luminous flux is emitted from the power of light sources. In other words, it can be described as relationship between light source output and its electrical input. Its unit is lumen per watt; lm/W.

Luminaire power density (LPD):

Lighting Power Density is the load of the lighting equipment in any defined space, or it can be defined as the watts per area (square meter) of the lighting equipment.

1.5. The Structure of Thesis

This thesis aims to estimate the most accurate locations, number and type of light sources in an office according to visual comfort conditions and energy efficicency by proposing a mathematical model. Prior to doing so the study is carried out seven phases:

Firstly, importance and necessity of designing energy efficient luminaire layouts in offices is defined by explaining studies conducted about the subject.

Secondly, general survey about lighting design and calculation methods of illumination is conducted. Researches about energy efficiency and technological development in lighting design are investigated and presented by considering optimum physical environment in offices. Also applications of optimization methods in building physics and lighting design process are explained.

In the third phase, based on the literature mentioned above a new optimization model named OptimLUM is proposed. The preliminary steps of this model is constructed in spreadsheets. A small cellular office is selected to statistically evaluate this steps. Illuminance calculation of the model is tested by a simulation program results; DIALux.

In the fourth phase, illuminance calculation formulas of the model are encoded in Visual Basics (VBA) to make OptimLUM run flexible at different room dimensions and with different luminaires. The prediction accuracy of interior illuminances carried out by OptimLUM is tested through comparison of the simulation results with measured data. Thus, the estimation performance of optimization model is empirically verified by getting measurements in a test case and by the DIALux models to explore its applicability and validity.

In the fifth phase, after the validation step, model should be developed to provide recommended conditions about office. There are sub phases about this progress.

- It is developed by adding parameters and constraints about illuminance ratios and luminance values on walls.
- Selected uniformity formula is tested by comparing other mostly used uniformity formula results.
- Luminaire database for OptimLUM users is conducted and selected room sizes to generate luminaire layout results is presented.

In the sixth phase, energy efficient luminaire layout solutions are produced and integrated with daylight to display number of luminaires during the daytime and for darkest conditions.

Last phase includes a discussion about the concluding remarks of estimated energy efficient luminaire layouts by OptimLUM and recommendations about the energy efficient lighting design. Significance of this proposed optimization model for early design is mentioned in order to provide optimal lighting design solutions.

CHAPTER 2

LITERATURE REVIEW

In this chapter, lighting design process is mentioned briefly and calculation of illumination and methods for modeling behavior of light are explained. Following sections include lighting systems based on lamp types and luminaires. In the context of energy efficiency in lighting design, technological development and researches are discussed considering optimum physical environment in offices. This chapter also includes applications of optimization methods in building physics and lighting design process.

2.1. Lighting Design Process

Lighting design is a layout process of light sources according to occupant's need, architectural features and functions. Lighting design process includes three steps which are data collection about space features and function, design of lighting project based on lighting technology and principles and finalization of light sources' layout (Çelebi 2007) The function of the space, the occupancy and architectural features guide lighting system choices. Selection of suitable combination of luminaire and lamp type is important to provide visual comfort needs and ambience of space. Variety of luminaires and lamp types can be selected together based on budget and light output characteristics. After decision of lighting systems; illuminance of the room and energy consumption of the systems are calculated and most accurate position of the system are finalized

2.1.1. Calculation of Illumination

An illuminance calculation includes mathematical processes performed in order to get illuminance levels provided by the lighting design. This calculation consists of mathematical formulations of physical phenomena related to the behavior of light (Çelebi 2007). These mathematical calculations guide designers to decide lighting sources' layout. Lighting calculations can be divided into two main groups.

Lumen Method:

Lumen method is used to get average illuminance on the reference surface. The indoor space is divided into three cavities which are ceiling, room and floor. The highest surface of these cavities is ceiling surface. The lowest surface which is assumed generally to be 0.85m above the floor is floor cavity. Middle surface is wall cavity that is between ceiling and floor cavity (The National Framework for Energy Efficiency (Australia) 2009). This method assumes that luminaires will be spaced in regular arrays which make uniform illumination. Lumen Method formulae is;

$$E_{wp} = \frac{\Phi_{total} \times CU \times LLF}{A_{wp}} \tag{2.1}$$

E_{wp}: Average maintained illuminance on the working plane

Φ_{total}: Total system lamp lumen output

CU: Coefficient of utilization

LLF: Light loss factor

A_{wp}: Area of the work plane

The efficiency of the luminaire, luminaire distribution, geometry of the space and reflectance ratios of the room surface are the factors that affect coefficient of utilization (Egan 1983). Lighting companies publish CU table for their luminaire which are specific to that luminaire’s light distribution and efficiency (The National Framework for Energy Efficiency (Australia) 2009). CU values are listed in tables based on different room geometries and reflectance ratios.

This method is limited to calculate illuminance for different luminaire layout due to some assumptions need to consider. All luminaires should be the same and be placed equally apart from each other with same orientation.

Point Method:

This method is based on illuminance at any point on observed surface. There are two components that have impact on illuminance level of this point. These are direct and indirect component of horizontal illuminance. Direct component is the effect of luminous intensity from light source on a point. Direct component is calculated according to the candle power distribution diagram of the lamp's luminous intensity. Direct component is calculated according to given formulae (2.2) is used. By repeating this formulae (2.2), for all calculation points of space, total direct illuminance would be calculated where **Φ** is total luminous flux of luminaire, I_{rel} is the luminous intensity on the point according to C-gamma angles (cd/klm), h is the vertical distance between the lamp and the point and α is the angle between these (Congradac et al. 2012).

$$E_h = \frac{\left(\frac{\Phi}{1000}\right) X\, I_{rel}\, X \cos^3 \alpha}{h^2} \tag{2.2}$$

Φ: Total luminous flux of luminaire

I_{rel}: Luminous intensity on the point according to C-gamma angles (cd/klm)

H: Vertical distance between the lamp and the point

α: Angle between the lamp and the point

Indirect component from the operation of the light occurs by reflecting from surfaces in the room. It is estimate to be uniform over all room surfaces.

$$E_{ind} = \frac{\emptyset}{\sum F_n} \times \frac{\rho_{avg}}{1-\rho_{avg}} \tag{2.3}$$

Ø : luminous flux leaving the luminaires

$\sum F_n$: total area of the room surfaces

ρ_{avg} : average reflectance of the room surfaces

Average reflectance is calculated by;

$$\rho_{avg} = \frac{\sum \rho_n F_n}{\sum F_n} \tag{2.4}$$

2.1.2. Lighting Systems

Lighting of offices is designed according to lighting quality, quantity, luminance and surface. These features are depending on function, dimensions and occupant number. Lighting sources should be selected according to these needs (Apaydin 2012). The selected light source should have high luminous efficacy, relative light efficiency, color rendering class and the index (Ra), continuous and smooth spectrum, long life, low energy cost, minimum maintenance, resistant (Bal 2005). Incandescent lamps, tungsten halogen lamps, fluorescent lamps, compact fluorescent lamps, compacted fluorescent lamps, metal halide lamps and LEDs are types of artificial lighting sources.

A lighting system can use energy efficiently not only by selecting energy efficient lamp but also selecting auxiliaries of the system such as efficient ballast, transformers, starters and dimmers. Auxiliaries of the system must have low losses for the high efficiency of a lighting system.

A luminaire diffuses, filters and transforms the light produced from one or more lamp. It contains all parts for supporting and protection of lamps. It is an equipment that consists of circuit hardware regulating power. The technologic development of the luminaires shows that the light from the lamp control with refractors and reflectors, losses of auxiliaries decrease with technologic electronic devices and efficiency of lamp increases with these developments. Today, luminaires for office buildings vary according to rendering values, quality of optical design, different volumes and properties of the materials (Apaydin 2012). The other equipment that affects the energy efficient lighting is control system. Many of control systems have been developed (Roisin et al. 2008). The most significant application area is office building. The goal of the control system is to reduce energy consumption by providing desired illumination at desired place and time. There are different types of these systems such as time lapse, occupancy sensor, daylight depended.

2.1.2.1. Lamp types

Our modern life is not effective without artificial light sources because of spending time indoors, traffic management and decorations. Lighting industry presents variety of lamp types according to their design, output and the way in which they produce light. With reference to production way of lamp, it can be categorized in three groups. They are; thermal light sources, discharge lamps and semiconductor light sources.

This section involves the various types of lamps, how they work and their advantages and disadvantages relating to their efficacy. The diagram below indicates the main groups of lamps mentioned (Figure 2.1).

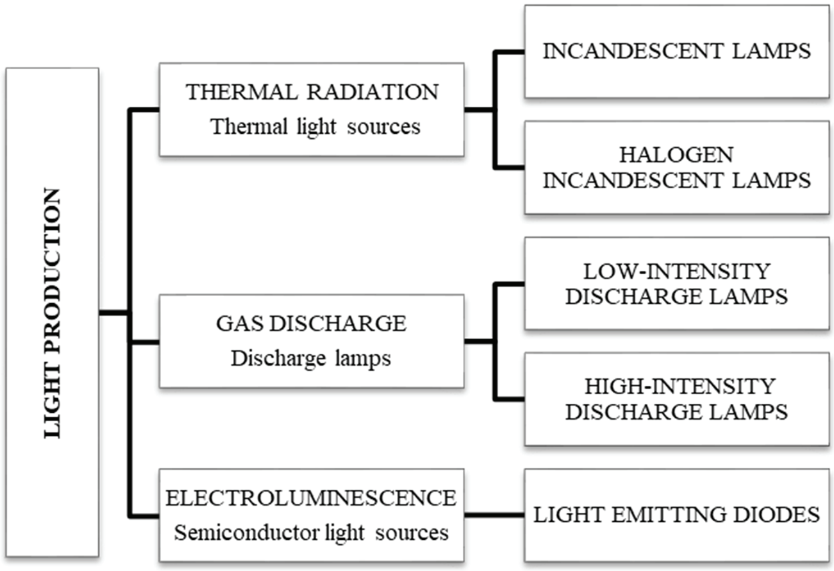

Figure 2.1. Lamp types according to light production.

- ***Thermal light sources***

  Incandescent lamp

Incandescent lamps convert electricity energy to heat. This energy raised temperature of filament until the lamp is incandescent. They are immediate on full brightness without extra equipment. But, such light sources are quite low efficiency because of high energy consumption values; 300 watts. However, due to very good color rendering values and cheap to buy they are still used (Apaydın, 2012). Today, they are not preferred in office buildings located in European countries because of high energy consumption, low efficacy and high running cost. China, Canada, United states, Colombia, Mexico, Cuba, Argentina, Brazil and Australia, they are banned to use.

Tungsten halogen lamp

Tungsten halogen lamp is developed to improve the efficacy and reduce the size of incandescent lamps. It has similar operating system with incandescent lamp, besides its light efficacy is higher than IL. Through halogen gas in the bulb, the filament temperature is getting higher and thus, the color temperature is also getting higher and whiter. It is used in retail and domestic areas, hospitality and for decorative applications (Zumtobel Lighting GmbH 2013), (IEA, ECBCS, and Annex 45 2010).

- ***Discharge lamps***

Fluorescent lamps (FL) and Compact fluorescent lamps (CFL)

Fluorescent lamps are the most commonly used light source in the offices. They convert the big amount of their energy consumed to light. Various color temperature and color rendering options are available (Apaydin 2012). They are more energy efficient than incandescent lamps by looking at the efficacy values of fluorescent lamp between 35-104 lm/watt. An alternating electrical field between two electrodes in the discharge tube produces invisible UV radiation. The tube's white fluorescent coating transforms this radiation into high-quality light. However it should be careful while recycling or disposal of this type of lamp due to containing unhealthy material; mercury (Aman et al. 2013). Other advantage of this type of lamp is that it takes time to spread full brightness.

Compact fluorescent lamp which is the compact variant of fluorescent lamp can be produced by development in lamp technology. They are commonly used in different spaces of offices except working and meeting areas (Emre 2012).

Metal halide lamp

Metal halide lamps are used in industrial bays and retail areas, not commonly used in offices. They have good color rendering and temperature, and different size options but their life is short (Emre 2012). By adding mixtures of metal components to the filling of the discharge tube, this type of lamp increases the luminous efficacy and CRI. These additives radiate their own line spectra in the arc discharge and emerge different colors of light.

High pressure sodium

High pressure sodium lamp is an elongated ceramic tube with sodium vapor. The produced light has a yellow hue and is only suitable for specific applications like outdoor and street illumination. I has good luminous efficacy and long lamp life (Zumtobel Lighting GmbH 2013).

- ***LEDs***

A light emitting diode (LED) is a ‘solid state’ electronic module only allows electrical current to move through diode in only one direction. With this flow, LED produces light of a specific color. LEDs can be assumed of as mini-luminaires. The LED luminaire includes a built-in reflector and lens, colored filters and scattering materials. LED (light emitting diode) is a new technological achievement for energy efficient lighting with an efficacy of more than 100 lm/W in the near future, a lifespan up to 50000 h and more, and with easy control and dimming options (The National Framework for Energy Efficiency (Australia) 2009) LEDs can be used for both functional and decorative lighting in indoor and outdoor locations.

2.1.2.2. Luminaires

There are two types of lighting which are general lighting and local lighting. General lighting supplies an approximately uniform illuminance over the whole working plane. The luminaries on these systems are arranged in regular layout. Local lighting differentiates from other by focusing small area occupied by tasks (CIBSE/SLL 2002). Both of them can be applied together (Çelik, Özcan, and Ünver 2014). Luminaire classification based on general lighting which is used for this study is explained in this section. According to CIE, there are six types of luminaires in general lighting. They are categorized according to the percentage of their luminous intensity direct toward ceiling and floor (Egan 1983) (Figure 2.2).

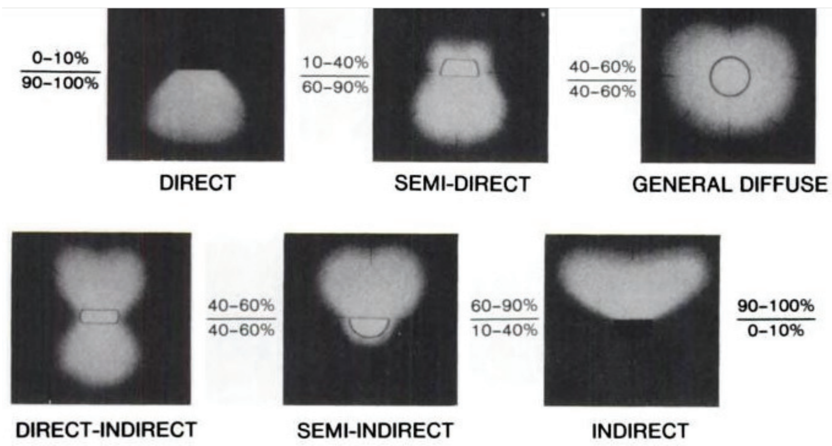

Figure 2.2. Types of luminaires in general lighting comfort (Chen 1990).

Direct:

Direct luminaires can be preferred to focus a specific plane. There are two types of direct luminaires; wide beam spread and highly concentrated beam spread luminaire based on providing different contrast level. These luminaires emits 90-100% of light downward (Chen 1990).

Semi direct:

Direct luminaires give rise to shadows on surfaces. Semi direct luminaire can soften these shadows and moderate contrast by spreading 60% to 90% of light to work plane (Egan 1983). By using it with reflectors and refractors it can be provide additional visual comfort (Chen 1990).

General diffuse:

Using these luminaires provide equal emission of light in all directions. Thus, it can make available to create stimulating, high brightness interior spaces (Egan 1983), (Gordon 2015).

Direct-indirect:

This type of luminaire can be used in spaces requiring equal light on ceiling and work plane.

Semi indirect:

Semi indirect luminaire can be selected for spaces requiring less direct light to balance illuminance of ceiling and work plane. By this way, it can be design a space of moderate contrast. 60% to 90% of emitted light is upwards (Egan 1983).

Indirect:

This type of luminaire is used to prevent dark ceilings and reduce shadows by reflecting luminous flux from ceiling to work plane. It provides uniform and softer ambient lighting. Its beam spreads from 80° to 120° upwards (Gordon 2015).

2.2. Energy Efficiency in Lighting Systems

Nowadays, due to developments in construction, technology and industry sectors, and need for comfort conditions, energy consumption rises. It is known that there is high amount of energy expenses of office buildings while they are in use. They are categorized among the buildings which have highest energy consumption. The significant amount of this consumption in offices is due to artificial. There are many researches about lighting offices. It is believed that energy savings of artificial lighting in offices has huge potential.

2.2.1. Technological Development of Lighting

A research about lighting in North Europe includes a literature review about energy savings of artificial lighting in offices. This literature review consists of many studies that use different methods such as; calculations, measurement, simulation etc. Their strategies are improvements in lamp, ballast and luminaire technology, use of task/ambient lighting, improvement in maintenance and utilization factor, reduction of maintained illuminance levels and total switch-on time, use of manual dimming and occupancy sensors (Dubois and Blomsterberg 2011). Most popular developments on lighting system are control systems and LEDs. There also some studies to show their performances and their effects on occupants' behavior. Li (2013) aims to reveal the effect of new developed lighting technologies usage in office. Author makes an experimental research which is established on a windowless office to analyze the impact of cutting-edge light-emitting diodes (LED) on the office ergonomics. Four lighting conditions and two levels of lighting control (with/without lighting control) are tested on 30 subjects. To understand subjects' approaches toward lighting quality and task satisfaction, a questionnaire is done. Contrary to general assumptions, the results prove the good lighting and color performance of LED. Other technological development; control systems and dimmers which are thought as useful for offices are tested on different researches. Another study designed a fuzzy logic controller according to daylight, users' movement and lighting comfort. A lighting system was set up in an office and the controller is experimentally tested by getting illuminance measurements (Liu et al. 2016). In Roisin et al.'s (2006) research, the goal is to analyze and optimize the lighting installations performances in offices. Many configurations of a typical room are simulated. Authors compared the models based on percentile effects of control systems, position of luminaires and sensors, use of blinds, fixed or variable presence to achieve energy efficient office. The result shows that a daylight dimming regulation is preferable to an occupancy sensor switching.

2.2.2. Daylighting in Offices

Development on lighting system is not only solution for reduction of energy consumption of artificial lighting but also for its integration with daylight. The natural light source; daylight should be considered to create healthy and efficient spaces. The previously mentioned control systems have several types such as occupancy sensor or daylight illumination level. Therefore, Galasiu and Veitch (2006) present a literature review about research studies on daylighting in offices. There are two themes that are; studies which examined the preferred physical and luminous conditions; and studies which investigated the occupant satisfaction by controlling artificial lighting and window shading elements in office environments. To summarize the research; the development of lighting and window shading control systems that are both energy efficient and suitable for the office occupants. Energy saving potential of different control systems is also a discussable research topic. Roisin et al. (2008) analyze the different control systems; daylight and occupancy sensor for a single office in three different locations in Europe. Simulation results show that daylight sensor has more energy saving potential that occupancy sensor.

2.2.3. Energy Efficiency and Occupants Comfort

The aim about energy efficient office is not only to reduce energy consumption but also provide occupants' satisfaction. To understand occupant's behavior and satisfaction, researchers make some observations, measurements and simulations. For this reason, a research goals to reveal the occupant's behavior effect over artificial lighting and natural lighting of single occupied office in Porto. Eight offices which have different plan scheme and workplace position are selected as case studies. When occupants are monitored, workplace illuminance, window and background luminance and transmitted solar radiation are measured with high frequency. Findings from comparison of monitoring and measurements show that occupants interact artificial lighting more than shading control. They opened shading devices in the morning and they provide desired illuminance with artificial lighting during the day (Silva, Leal, and Andersen 2013). This solution notices the awareness and willingness of occupants about energy efficiency. Countries have been published their standards, codes and recommendations. Moreover, engineers still continue to develop technology and architectures create energy efficient spaces. A study is deal with to show managers 'awareness about the usage of spaces and technologic equipment, occupants' control on the lighting. A review is conducted about lighting energy saving, energy efficiency policies and practices in office buildings in Greece. 685 face to face surveys are carried out to reveal their knowledge about energy awareness. The data about square meters, construction year, percentage of energy efficient lamps and energy cost of building; also age, education and business activity of respondent are collected. Their willingness to apply energy efficient lamps, occupancy lighting sensors and date efficient systems are asked. The results of the study shows that managers have willingness to apply energy efficient systems, the occupant should be educated and lighting systems of old buildings should be renovated (Zografakis, Karyotakis, and Tsagarakis 2012). Another study about occupants' preferences about energy efficiency is established in Swiss. By considering evening office lighting, authors compare two different energy efficient lighting scenarios. One of them is more energy efficient than other office, provides higher work plane illuminance but gives rise to risk of discomfort glare. 20 human subjects; 10 male and 10 female people; are observed during approximately a month. Participants' concentration and performances on computer and paper are tested. Participants rate questionnaire about their visual comfort. According to occupant preferences, comparison of the results shows that the positive effects of higher work- plane illuminance are stronger than the negative effects of discomfort glare when working under artificial lighting conditions during in the evening hours (Linhart and Scartezzini 2011). This article also display that occupants may desire different illumination levels based on local conditions although international standard and recommendations have been published. Solar radiation levels and benefit from sunlight are different in cold climate region and hot climate region. There is a study discuss these differences by conducting a research about illuminance of office in Sri Lanka. Different participants are selected according to different ages, professionals and considering their office working background and geographical locations within the country. They are subjected to ophthalmological test and visual performance test in a simulated office. Authors conclude this research by saying that illumination levels can be lower in hot clime regions than the illumination standards. By this way, offices in Sri-Lanka can be more energy efficient (Wijayatunga, Fernando, and Ranasinghe 2003).

2.2.4. Daylight and Artificial Lighting Integration

Integration of daylight and artificial light for energy efficient lighting in offices is widely mentioned in the literature. Energy efficiency of building is defined by also some architectural design criteria. The most effective criteria in lighting is about glazing that includes windows and shades. Size, orientation, transparency and frame transparency of glazed surfaces may improve the energy efficiency of buildings in terms of light and heat or vice versa. While sizing windows in hot regions, principles of the passive heating and cooling systems should be taken into consideration. Orientation may also solve the heating and lighting problem (Al-Sallal 1998). Persson, Roos, and Wall (2006) points out that the size of windows is not very effective for the heating purpose for winter conditions but it is more related to the cooling demand in summer. The size of windows facing to south should be determined according to the optimum sizes to prevent overheating and to minimize cooling loads. Glass type is as important as the area of the glass surface and its orientation. Glasses which are used to control light and heat may be heat absorbing-tinted glass, reflective glass, low-e glass, spectrally selective glass, polyester film coating, heat mirror glass, smart-switchable glass and inert gas inter gap of glasses (Smeds and Wall 2007), (Soysal 2008). There are some researches about the effect of glazing types and dimensions on energy savings due to integration of daylight and artificial light. One of them is conducted for Saudi Arabia. The problem of this study is that lighting offices by only artificial lighting in hot climate causes to increase cooling loads and daylight by itself is not enough to provide a uniform illuminance. Artificial and daylight implementation on lighting of offices may provide decrease in energy loads especially in lighting energy. Thermal and lighting models of an office building are simulated. Different type of windows' configurations and glazing type performed in these simulations. This results of the study shows that window to wall ratio is more significant but the effect of glazing type is not small to ignore (Al-Ashwal and Budaiwi 2011). Another study in hot climate region aims to expose the potential of natural light usage in office because lighting of the offices in Malaysia is supplied by artificial light sources and the bright daylight can disturb the workers. Author makes some measurements in Malaysian offices. Workers reply a questionnaire about their visual comfort and satisfaction. These offices are simulated. The result of this study shows that there is potential of daylight in hot-climate by using special glazing (Denan 2004). These studies prove that in hot climate region where the buildings consume more energy for cooling, daylight control and the effect of artificial lighting on cooling load are important for optimum energy consumption and comfort conditions. Integration of daylight and artificial lighting is unavoidable not only for hot climate but also cold climate region. The offices in different locations should have an appropriate lighting that includes daylight and artificial lighting. An office building is selected as case building and it is simulated on four different regions in U.S. to show this integration. Building geometry, window area, window type, and perimeter area are analyzed by parametric analysis. Simplified method consists of the variables correlation coefficients. By this way, designers can apply the offered simplified method to their design for calculating the potential lighting energy reduction from daylighting.

The other criteria that can control daylight and help to uniform illuminance indoor, is solar shades. The level of light and temperature which is required for the interior space may be provided by using solar shades with glass. Seasonal and orbital sun angles are determinants for the reflection of direct light coming from the sun. Flexible and movable sun shading devices display a high- sun-control performance. "Different solar shades, shutters, blinds, insulated shutters, awnings, jalousie and curtains as well as deep balconies, horizontal canopies, vertical sun breakers- wing walls, composite elements which are the combination of vertical and horizontal components are used for the solar control" (Soysal 2008). The manual shading devices is not preferable today. Da Silva's study shows us that occupant do not control their shading devices according to daylight. They prefer to switch on/off light sources. Automated sun shades are also new developed device. Alzoubi (2005) studied on this purpose on his thesis. Author of the thesis seeks to develop an automated method for optimization for lighting, thermal performance and energy production of the building. This automated method utilizes solar energy while providing optimal solutions for indoor daylighting. System focuses on the building façade, especially window and shading. A full-scale mock-up office is built to measure heat gain and lighting interrelated with blind angles. In the same time the power production from photovoltaic cells is compute. According to results of the experiments mathematical formulas are created. These formulas are used for optimization and coded on Java. This system calibrates the blind angles instantaneously based upon the sun position, the indoor daylight, and the power production from the photovoltaic cells. The system is the proof of controlling projected solar energy on buildings' facades for indoor lighting, heat gain and that the optimality of building facades' performance is possible.

All studies about energy efficient lighting for offices shows that, technological development and researches will be continue. There are many things to achieve optimum physical environment in offices. Engineers, architects, office managers and also occupants are responsible on this issue.

2.3. Optimization

Optimization is a progress to find most appropriate solution for a problem having many conceivable solutions. The aim of optimization is to minimize the essential effort or to maximize the desired benefit. This minimization or maximization can be described as a function of certain decision variables. The minimum or maximum value of these functions is the result of optimization process. It can be understood that optimization problem includes many variables that work together based on given formulas and constraints. Designing an optimization problem begins by formulating variables which involves many highly sensitive parameters for working model properly. They can be fixed or vary during the process. Selecting accurate variables can increase efficiency of the model (Kalyanmoy 2012).

After designing variables and other parameters, constraints can be identified as resource limitations. Constraints are conditions must be entered for a solution to be valid. Constraints require static or dynamic equilibrium using <,<=, >, >= or = relations (Palisade Corporation 2013).

Third step of the designing optimization problem is determining optimization goal in other words; objective function. Optimization goal can be described what kind of answer designer search for. There are two types of objective functions which are minimization and maximization. Minimization means searching for the variable values that produce the smallest possible value for the objective function. Maximization means searching for the variable values that produce the largest possible value for the objective function (Palisade Corporation 2013).

"A classical approach to solution of optimization problems has three steps,

a. Find necessary conditions that the optimum must satisfy by using differential properties of certain optimal solutions,
b. Solve the equations that constitute the necessary conditions to obtain candidates for optimum,
c. Test the candidates for the optimum by using necessary and sufficient condition test." (Pierre 1986)

According these steps, it can be understood that huge number of solutions are tested and this is accomplished with an algorithm. This algorithm is the description of the way of approaching the problem. Finally, result of the optimization method gives the solution as close as possible to the value you specify (Palisade Corporation 2013).

2.3.1 Optimization in Building Physics

Due to the fuel crisis in 1970s, energy efficiency has been a critical issue to reduce energy cost and to ensure sustainability of energy throughout the world. As the building is the main source for energy and resource consumption in world, design and operations of buildings have gained utmost concern nowadays to reduce energy and resource consumption. Researchers and relevant people in the sector endeavor to reduce energy consumption and provide optimal comfortable spaces. The interest to application of optimization method is growing in built environment, especially in building physics.

Optimization is the process of obtaining the best under many possible solutions (Palisade Corporation 2013). For this reason, researcher use optimization method for wide range of the problems in this research area to be solved. One of these problems is to reduce heating energy consumption by providing thermal comfort of occupants. HVAC system is an active system that supplies thermal energy and ventilation of indoor environment. A research is conducted on optimization of thermal comfort and energy consumption in a residential house. Simulation based Artificial Neural Network (ANN) is used to take variables from HVAC system settings, thermostat programming, and passive solar design. Results of the optimizations display that significant amount of energy consumption decrease while thermal comfort improves (Magnier and Haghighat 2010). These active systems are selected according to many criteria such as building types, dimensions and cost. A study is about to get an optimum solution for operating cost and thermal comfort based on HVAC systems (Wright and Loosemore 2001). Indoor air quality is an also important factor for buildings by providing desired temperature level for occupants. Zhou and Haghighat (2009) create optimization formula over these air quality, thermal comfort and energy consumption in offices.

These mentioned systems are not only equipment to provide thermal comfort of buildings. Before the construction, designers decide some architectural criteria that effect building environment and energy consumption. Diakaki et al. (2010) develop a multi-objective decision model for the improvement of energy efficiency in buildings. Simulation and multiple criteria decision analysis techniques are used to get the effects of the type of the building's door and window; the structure of the building's walls, ceiling and floor the thicknesses and corresponding materials to be used in the building's walls, ceiling and floor insulation layers; the space heating system; the space cooling system; the hot water supply system(s). These effects are used in optimization method by considering energy consumption of building.

Glazing is a significant architectural criterion on energy efficiency for new and also renovated buildings considering thermal and visual comfort. Huang et al. (2014) successfully demonstrate an optimization method can be applied for renovation of existing buildings. Window to wall ratio and thermal properties of window are objectives of the research to calculate optimum energy performance of envelope. Mathematical model is conducted on model of thermal insulation thickness of external wall economically by considering the impact of orientation. Limits of heat consumptions of buildings are related to China national standard and climatic zones of China (Huang et al. 2014). This optimization project is a good sample in energy research area by taking notice to existing buildings. Although benefit from daylight is desired, its effect on heating and cooling load cannot be ignored: The objectives of another study about optimal envelope for energy consumption and daylight are the daylight duration, the heating and cooling loads. The façade of a dormitory is chosen as a case study. The variables of the problem are window type and the window-to-wall area ratio. DAYSIM and Radiance simulation programs are used for calculation of illumination. The Pareto-optimization is selected for optimizing strongly non-linear and uncoupled functions. This research notice both thermal and visual comfort together by considering energy consumption (Lartigue, Lasternas, and Loftness 2013).

While some researchers try get optimal solution in building physics area, some of them intend to integrate this optimization method into simulation tools. For this reason, M Mourshed, Kelliher, and Keane (2003) go into detail on the previous researches which attempt to integrate the design process and simulation and make some the limitations. Then, optimization formula is crated based on different stages of design. Stakeholders and processes, the use of client/ server oriented building product model has been offered to decide the limitations of file-based prototypes. Authors wish that if “Architectural Design Optimization Tool” will be successful, it will be a good decision making tool for the design of energy efficient buildings. (M Mourshed, Kelliher, and Keane 2003).

Some researchers code optimization formulas to a building which has automated system. Hussain Hendi Alzoubi (2005) develops an automated method for optimization for lighting, thermal performance and energy production of the building. This automated method utilizes solar energy while providing optimal solutions for indoor daylighting. System focuses on the building façade, especially window and shading. A full-scale mock-up office is built to measure heat gain and lighting interrelated with blind angles. In the same time the power production from photovoltaic cells is compute. According to results of the experiments mathematical formulas are created. These formulas are used for optimization and coded on Java. This system calibrates the blind angles instantaneously based upon the sun position, the indoor daylight, and the power production from the photovoltaic cells. The system is the proof of controlling projected solar energy on buildings’ facades for indoor lighting, heat gain and that the optimality of building facades’ performance is possible (Alzoubi 2005).

Optimization method is not only used for optimum solution for reducing building energy consumption and providing comfort conditions but also is applied energy quality management of these supplies and demand. Energy quality management has become important in a field of energy by improving the energy efficiency, reducing energy consumption and improving the match between energy supply and demand. Lu et al.’s

(2014) research aims to minimize the global warming potential during the life-cycle and maximize the energy performance, while the maximum allowable level of the loss of power supply probability is predefined. This optimization model is constructed by Genetic Algorithm. Office building clusters and districts located in Norway is selected as case study. This case study proves that purposes about energy quality can be accessible by using optimization method (Lu, Alanne, and Martinac 2014).

2.3.2 . Optimization in Lighting Design

Lighting has been an inseparable from architecture through the history but it is accepted as science recently by understanding the nature of light, explaining by equations. Lighting design of space is a complicated task that includes multiple criteria. There are several methods used in illumination design. One of them is lumen method which is commonly used but cannot calculate other complexities of illumination of space. Thus, new realistic methods were developed by computer graphics and these methods use engineering computational tools and architectural rendering. Nevertheless, lighting designers cannot design an accurate lighting system which provides desired illuminance levels. Researchers continue searching and using different methods to find optimum solutions for visual comfort of occupants; to get uniform illuminance, prevent glare, control daylight and artificial light by considering energy performance of buildings. Researchers commence to use optimization method recently in lighting research area.

2.3.2.1. Application in Artificial Lighting Design

Designers decide the locations of luminaires by estimating illuminance levels but they cannot achieve accurate location. H. Rocha et al. 2016 propose a computer-automated design tool for exterior lighting design. The proposed tool, named ELCAutoD-EA, which is based on multi-criteria parallel evolutionary algorithm (based on heuristics) optimizes designs for illumination quality and energy efficiency by decreasing luminaire power consumption. H. Rocha et al. present a case study on an available private parking lots of the airport of Uberlandia (Brazil) to test the developed model. The given illumination design solution by ELCAutoD-EA and existing lighting system performance were evaluated by getting quality measurements for both lighting systems. This tool illustrate the possibility of better uniform illumination and energy efficient layout(Rocha et al. 2016). Cassol et al. (2011) introduce a new methodology to estimate locations of light sources by using the generalized extremal optimization (GEO) which is similar to genetic algorithm. Inverse design technique which was used to solve similar problems occur in thermal design area is applied in this article. This proposed multi- objective optimization formulation provides the accuracy of the illuminance on the work plane and of the total luminous power. It includes three dimensions of the space; walls, light sources, work plane. By the way, the incident illuminance on the work plane and reflections of the light in all surfaces can be computed. The pioneer article about this inverse illumination design belongs to (Tena and Rudomin 1997). Optimization technique of this study is genetic algorithm. Computer programs which can render 3D illumination of spaces are used. Radiosity method is used for illumination of surfaces. The aim of this study is to solve inverse illumination problem and find the best configuration of lights (level, position, number of lights and cost). Different optimization techniques are applied to this inverse analysis to find illumination levels of spaces. As an example, Schneider et al. (2009) applied inverse analysis to illumination design, considering three dimensional enclosure. There are two different approaches. The first one is based on an implicit formulation which relies on the specification of the luminous powers of the light sources, then finding the luminous flux on the design surface. And second one is Stochastic-based optimization technique. The light sources of this article are incandescent lamps. Two different case are designed. Two approaches for solution of the problem are compared. Errors of the obtained solutions were <3.0%.

Different researches benefit from simulation programs by estimating luminaire position because these programs support designer to decide locations of light sources with many alternatives. Monjur Mourshed, Shikder, and Price (2011)'s study proffer an optimization methodology. Authors use simulation program; Radiance, and Genetic Algorithm for optimization process. Horizontal illuminance analysis performed with a frame which is composed with illumination values of reference points. Similar gridal frame is applied for lighting source locations. The both luminance on the horizontal and vertical surfaces are analyzed by simulation program. These three dimensional data is evaluated by phi-array method.

Desired illuminance level changes according to task. In open plan offices, office workers carry out their jobs in their own desks which are located in one space. Energy saving of office lighting can be reduced by implementing task lighting. Every occupant can work under their desired lighting and also, their satisfaction and motivation can increase. Wen and Agogino (2011) seeks a new method for complementing net-worked lighting system which is dynamically tuning task lighting to each worker's preference with maximum energy savings. Authors establish the formula into linear programming. They also use simulation programs to show encouraging performance of this model and the resulting energy savings in different scenarios.

2.3.2.2. Application in Daylight Design

Optimization method is also used for lighting calculations about daylight. Daylight is effected on heating, cooling and lighting loads of spaces. (Shikder, Mourshed, and Price (2010) focus on optimization of window configuration considering daylight and thermal conditions. Size, orientation and shading are the most important parameters for window design. Some assumptions are determined for this study; these are tall pane of glass and a light shelf, and orientation of window toward the South. Four parameters; the width, sill and lintel level heights, and the depth of the solar shading, define window. Daylight factor and annual cooling/heating loads establish performance of window. Radiance is used for lighting simulation and Autodesk Ecotect is run for thermal simulation. 810 combinations are crated. Based on the data from simulations programs, a normalization formula for daylight levels and cooling/heating loads is generated (Shikder, Mourshed, and Price 2010). Another study about window sizes are conducted by Wright and Mourshed (2009). This research is an example of application optimization model in energy efficiency of buildings. The aim of this study is to investigate optimum fenestration design because it effects daylight penetration, artificial lighting energy use, and heating and cooling energy use. This methodology can optimize the shape, number, and position of windows by minimizing building energy use. Façade of the building is divided into number of small cells. Each cell has two possible states; solid construction, or glazed construction. A "window" on the façade is defined to be a set of adjoining cells. The number, position, total percentage area, cellular density, and aspect ratio of such windows are developed as metrics. The metrics which are found by the optimization are used in the analysis of the design solutions. Three optimization model are created in this paper. First model is an unconstrained minimization of building energy use. Second and third model are based on two constrained minimizations of energy use, the first with the window aspect ratio constrained, and the second with the number of windows constrained. These three experiments are solved by Genetic Algorithm. The three solutions are different from each other (Wright and Mourshed 2009).

Natural light source is irreplaceable and it changes during the day and the year. For this reason, De Rosa et al. 2009 propose new code about prediction of daylight illuminance on the inside surfaces which name is INLUX was validated by comparing its calculated illuminance with illuminance measurements inside a scale model 1:5 (De Rosa et al. 2009). Because of the unpredictability of the daylight, this natural light should be controlled with shading devices, light control systems to provide comfortable indoor environment for occupants. Uniformity of lighting, glare, high luminance reflections and energy consumption should be evaluated together. De Carli and De Giuli (2009) aim to develop the quality of visual comfort and to minimize lighting, heating and cooling loads. An office where four people work together is selected as a case study and it is simulated on software DAYSIM. There are some assumptions which are: the geometry of the room, the material of the surfaces' room, the climate file and the position of the sensors. Different shading devices are created and control system is used. This article evaluates impact of shading devices, control systems on illuminance in work places, daylight factor and energy consumptions (De Carli and De Giuli 2009).

2.3.2.3. Application in Integrated Lighting Design

Lighting design which is significant based on energy efficiency consists of natural and artificial lights. Fernandez and Besuievsky (2012) provide a tool for artificial light sources and skylight installations. Previously mentioned inverse lighting method is used to estimate optimal light source positions and optimal shapes for skylight installations in interior spaces. Optimization formula is established on economical solutions of artificial light sources and maximal global light-power solution. Authors developed a new technique of inverse lighting by assembling the use of an optimization metaheuristic with the LRR technique as a radiosity solver. The paper discourses optimization problem with constraints, using the penalty method (Fernández and Besuievsky 2012). Illuminance level should not change substantially. Artificial lighting level may be dimmable according to natural light level. By the way, there will be increase of energy efficiency by using daylight. Čongradac et al. (2012) develop a model for the control of dimmable lighting. Authors explain the calculation of the horizontal lighting at any point in the room on the work surface due to the effect of lamps and light reflection from the walls, floors and ceiling to understand the establishment of the mathematical model. A genetic algorithm model is applied for the control of lighting by continuous light dimming. This model is tested by MATLAB software based on the designed mathematical model and the assumed daylight changes (Congradac et al. 2012).

CHAPTER 3

PRELIMINARY MODEL (OptimLUM)

This study is formulated under the purpose of constructing model named OptimLUM (Optimizing luminaire layouts) to estimate the most accurate location, number and type of artificial light sources according to average illuminance and maximum uniformity in an office. The other objective is to test the calculation process of the model and its estimation about luminaire locations. A small cellular office is selected to construct the preliminary steps of OptimLUM. A simulation program; DIALux is used to evaluate illuminance calculation of the model. In this section, the procedure of the research is introduced to achieve these objectives.

3.1. Preliminary Model (OptimLUM) Construction

Firstly, a problem case has been selected to build the phases and to practice the mathematical model. The room was intended to represent a small cellular office and measured 5.80 m in the x-direction and 4.20 m in the y-direction. The ceiling height was 3.3 m. The measurement plane was 0.80 m above the floor. Calculation points were placed at least 0.5 m away from the surface of the walls. There were 81 calculation points by giving spaces 0.6 m between them in the x-direction and 0.4 m in the y-direction (Figure 3.1.)

Locations of light source were constructed out based on ceiling tiles of size 600x600 mm. Recessed mounted modular luminaires have been selected according to architectural qualities of the space. There were 54 different points to estimate location of light source (Figure 3.2).

Location points of luminaires and calculation points are not aligned to capture the distribution angles of the luminaire extensively and to obtain dissimilar illuminance levels at each calculation points (Figure 3.3). Non-aligned location grids were used in previous studies (Monjur Mourshed, Shikder, and Price 2011), (Shikder, Mourshed, and Price 2010b).

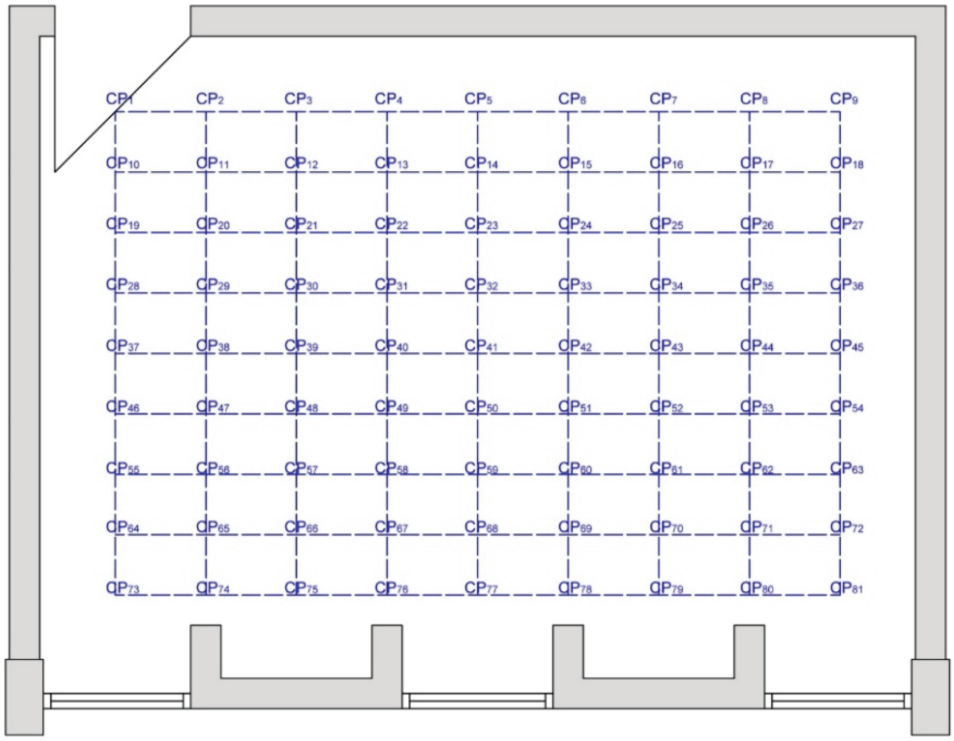

Figure 3.1. Calculation points of preliminary model case.

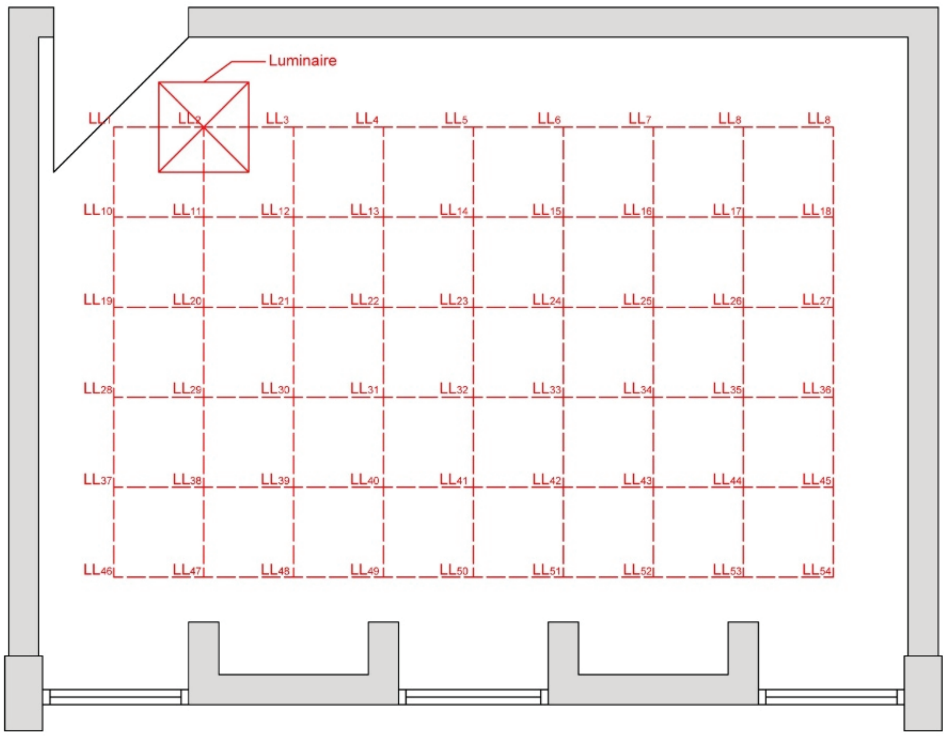

Figure 3.2. Location points of light source in preliminary model case

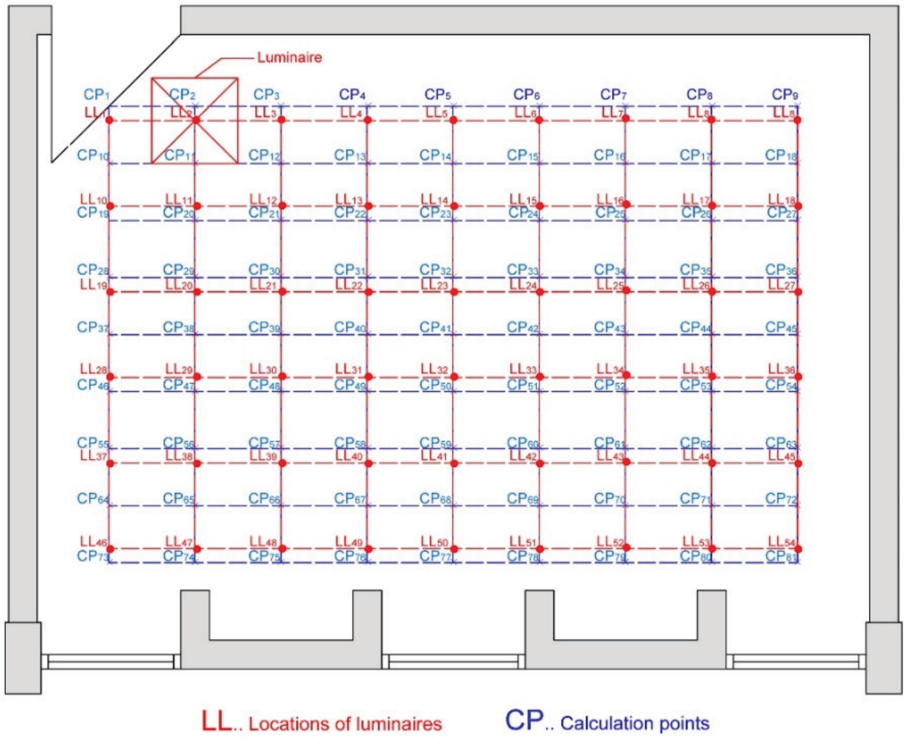

Figure 3.3. Luminaire location points and calculation points in preliminary model case.

3.2. Method

This subsection includes spreadsheet steps, problem formulation on Evolver and explanation of validation process.

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3.2.1 Spreadsheet Steps

A mathematical model was created and developed for this optimization problem. An Excel spreadsheet was used as a base of the model because of its simpler and transparent approach to modelling. This spreadsheet included 5 steps.

Step 1. The first step of this model was the construction of the locations of points on the working plane and ceiling. Their co-ordinates on x, y and z plane were entered to the model according to point of 0, 0, 0 on left and top side of the room. C and gamma angles between calculation points of model case and location points of light source were calculated.

Step2. Luminous intensity of luminaires which varies according to C and Gamma angles composes photometric data. DIALux provided such data to be imported in this model.

Step 3. This step included composing information about total luminous flux of selected luminaire, data about room dimensions (height, width and length), and reflectance of wall, ceiling and floor. This type of data is interchangeable easily to create different lighting scenarios for the same room. For this reference room reflectance of wall, ceiling and floor are 0.50, 0.70 and 0.20 respectively.

Step 4. This step is the calculation process. The model calculates total illuminance of the points (the summation of reflected and direct illuminance), which varies according to the light source location scenario. The point method has been used to calculate illuminance at calculation points on the working plane.

Step 5. Based on recommendations about working places, the average illuminance level is 300-500 lx. According to the illuminance level at calculation points, the average illuminance level on the working plane was calculated by the division of total illuminance by the number of points. On the other hand, the main goal of the study, after having desired light intensity, is to provide uniform illuminance on the working plane. The mean relative deviation (MRD) was used for this problem to calculate relative deviation of illuminance level at the point from average level of whole space (Ferentinos and Albright 2005).

3.2.2. Problem Formulation

The design variables of the study were the positions of selected luminaires on the x plane. The luminaire is recessed mounted type (4 x 14 W – 64.6W) which is 600 x 600 mm in dimension. The problem involves two scenarios; one including two luminaires and the other including three luminaires. There are a total of 54 different positions to locate the luminaires and 81 horizontal calculation points which are on the working plane. The illuminance levels resulting from these two scenarios were analyzed to define their optimal positions.

The primary objective of the research is to get illuminance uniformity (3.1) on the working plane with two constraints (3.2, 3.3). I_{avg} is the average illuminance level of working place. I_i is the illuminance level at one calculation point, and I_m is the mean of illuminance level at all these points.

Minimize:

$$MRD = \frac{\sum_{i=1}^{N} |I_i - I_m|}{NI} \tag{3.1}$$

Subject to:

$$I_{avg} \geq 300 \text{ Lux} \tag{3.2}$$

$$I_{avg} \leq 500 \text{ Lux} \tag{3.3}$$

To solve this optimization problem, Evolver 6 was used as optimizer in this study. Evolver applies genetic algorithm-based optimization techniques to find optimal solutions for standard linear and non-linear problems. This program is used as an add-in to Microsoft Excel spreadsheet program to solve problems set up in spreadsheets (Evolver 6) (Palisade Corporation 2013).

3.3. Results

Before the optimization process, the illuminance calculation of mathematical model was evaluated comparing by DIALux findings. The validation process of illuminance calculation of the model involves the formulation of a linear regression line to compare the simulation and mathematical model illuminance levels at each calculation points for two luminaire locations and observe the strength of their relationship. Coefficient of determination (R^2), root mean square error (RMSE), normalized root mean square error (NRMSE) and coefficient of variation (CV) are calculated for two luminaire locations. Scatter diagram is developed to figure out whether the mathematical model fits the simulation model or not. Considering the photometric data, the luminous intensity of luminaire is 4264 lm (Figure 3.4).

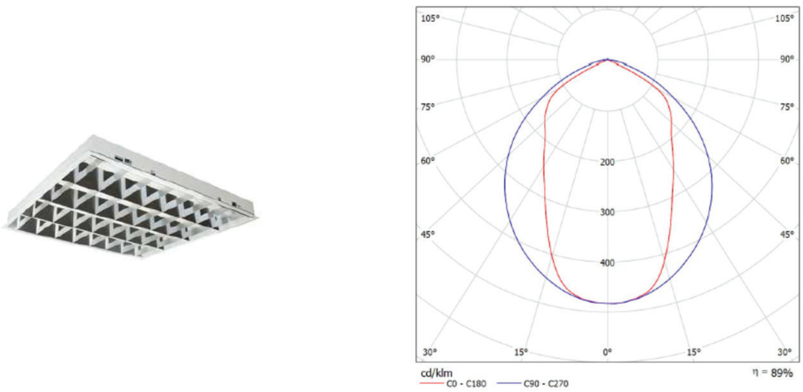


Figure 3.4. Data sheet of selected luminaire for preliminary study.

Model was performed at two different specific luminaire locations. Illuminance level at calculation points on the work plane was calculated for one luminaire at LL_{23} and LL_{32}. Luminaire was located at similar positions in DIALux model. Outputs of the mathematical model were higher than the ones in the simulation (Figure 3.5). To compare them quantitatively, R^2 was almost 88 % at for all results, showing the high accuracy of the mathematical model. This meant that knowing the illuminance at points by the mathematical model gives an almost 88% chance of predicting their values on the simulation model (Figure 3.6). To observe differences between outputs and model results at two luminaire locations, RMSE was 42.82 and 43.09 respectively. NRMSE and CV were 0.14 and 0.26.

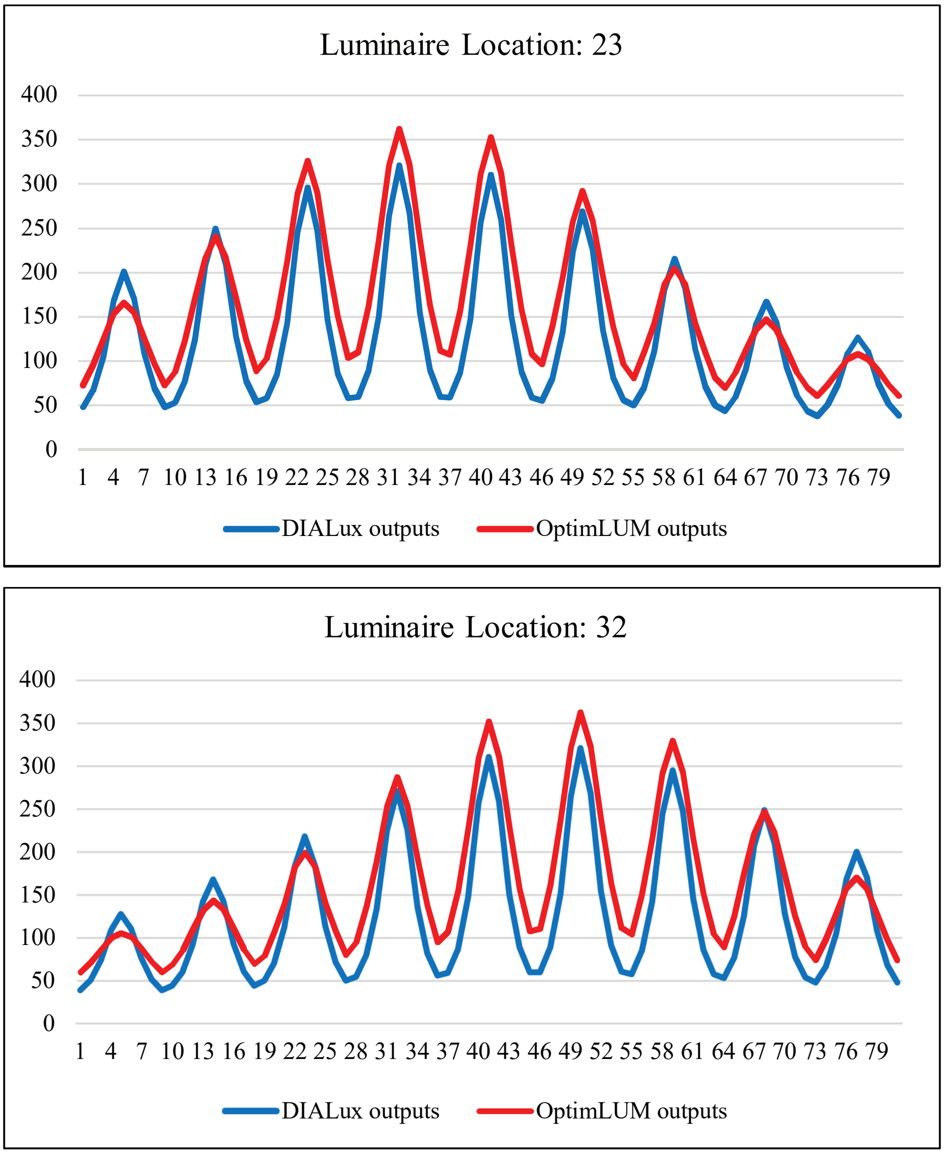
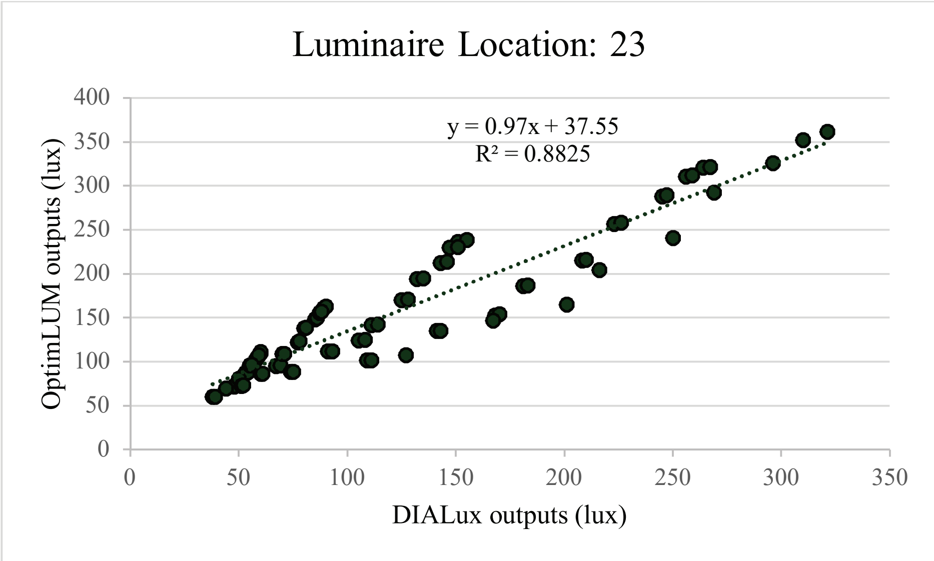


Figure 3.5. Comparison of illuminance distribution at calculation points.



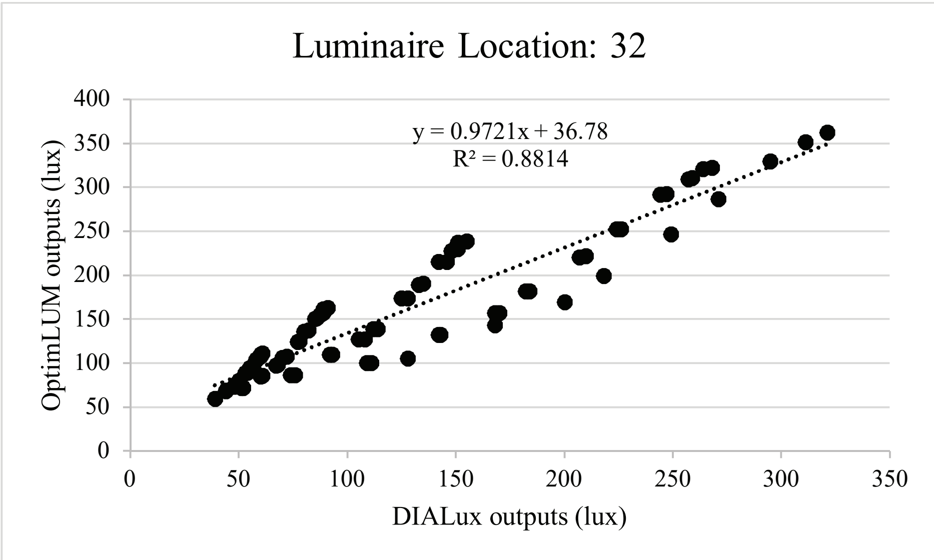
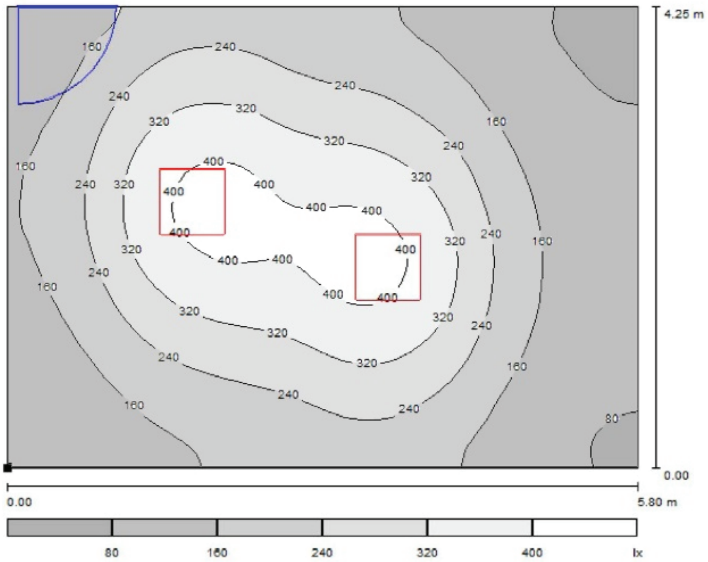


Figure 3.6. Scatter diagram of illuminance distribution at calculation points.

After the validation step, the optimizer tool employs to solve this optimization problem while using the same luminaire. According to results of the first scenario, which was to identify the best position of these two luminaires meeting recommended horizontal illuminance requirements, the average illuminance (E_{avg}) is 306.71 lx and uniformity (MRD) is 0.31. Locations of this optimization problem were simulated in DIALux and their average illuminance is 224 lx and E_{min}/E_{avg} is 0.28 (Table 3.1).

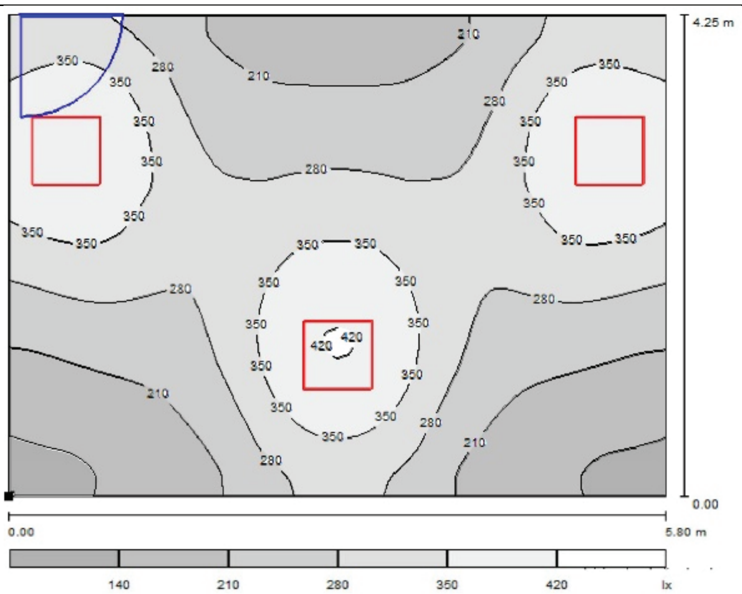
The second scenario, which was to identify the best position of three luminaires, resulted in better uniformity with higher illuminance level. E_{avg} is 363.87 lx and uniformity (MRD) is 0.13. By conducting the simulation for the second scenario, E_{avg} increased to 283 lx and better uniformity with E_{min}/E_m is 0.46 was obtained (Table 3.2).

Table 3.1. Illuminance distribution with location of luminaires in the first scenario and E_{avg} and two uniformity results of OptimLUM and DIALux



OptimLUM		**DIALux**	
E_{avg}	306.71 lx	**E_{avg}**	224 lx
U (MRD)	0.31	**U (E_{min}/ E_{avg})**	0.13

Table 3.2. Illuminance distribution with location of luminaires in the second scenario and E_{avg} and two uniformity results of OptimLUM and DIALux.



OptimLUM		**DIALux**	
E_{avg}	363.87 lx	**E_{avg}**	283 lx
U (MRD)	0.13	**U (E_{min}/ E_{avg})**	0.46

In an earlier study (Monjur Mourshed, Shikder, and Price 2011), researchers tried to find optimum positions for two different luminaires in two identified and smaller/limited areas. Apart from that study, the optimization study focused on finding the optimum positions of two luminaires in Scenario 1 and three luminaires in Scenario 2 in one identified and determinate area. Thus, their mutual impact while calculating the illuminance and uniformity is integrated in the optimization model. The optimization model in this case performs well in locating and determining the luminaire positions. It presents a high accuracy with the outputs of DIALux model.

CHAPTER 4

VALIDATION PROCESS

The main objective of this chapter is to evaluate the prediction accuracy of interior illuminances carried out by OptimLUM through comparison of the simulation results with measured data. Thus, the performance of optimization model named OptimLUM is empirically tested by getting measurements in a test case and by the DIALux models to explore its applicability and validity.

4.1. Determination of Existing Office

The study is carried out in an office (106) located in a 2-story building (Block C) at Faculty of Architecture, İzmir Institute of Technology, Turkey. This office building is situated in latitude 38° 19”; longitude 26° 37” (Figure 4.1). The office dimensions are 5.33 m in the x-direction and 3.32 m in the y-direction. The ceiling height was 2.9 m.

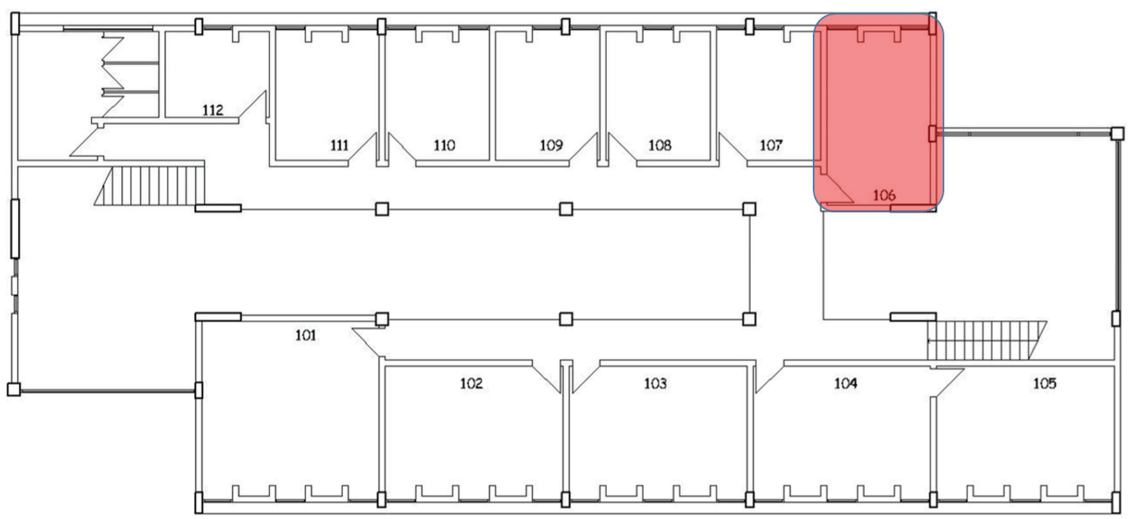


Figure 4.1. Selected room location in the floor plan of office building.

4.1.1. Existing Office Environment

The office has three brick walls and one yellow painted wall. Ceiling is concrete and ground material is marble. The windows have their own interior and exterior shading systems which are used to block sunlight (blinds).

Figure 4.2. Test case and shading systems

The reflectance values for walls, floor and ceiling were measured by luminance meter and calculated according to the formula (4.1) (Fontoynont and Berrutto 1997). ρ_s is the reflectance value of surface, ρ_{white} is the reflectance value of white surface, $L_{surface}$ is luminance of measured surface and L_{white} is luminance of white surface. According to these measurements, ρ_{wall} was calculated as 0.37, $\rho_{ceiling}$ as 0.27 and ρ_{floor} as 0.60 (Table 4.1).

$$\rho_s = \rho_{white} \frac{L_{surface}}{L_{white}} \tag{4.1}$$

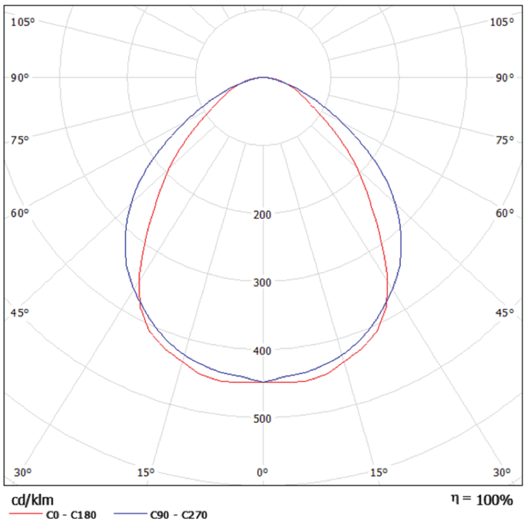
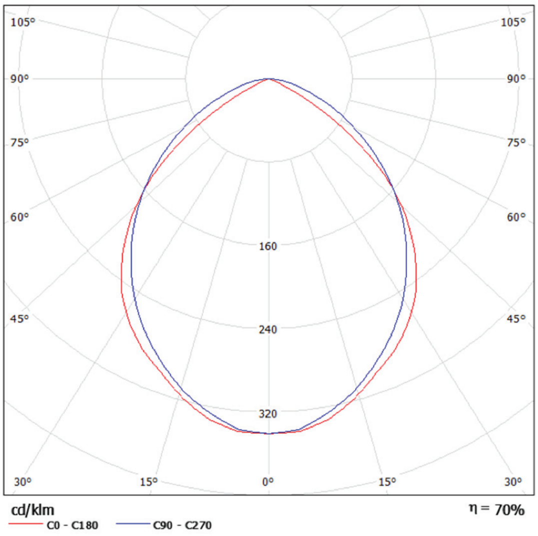
Table 4.1. Reflectance of surface materials

<table>
<tr><th colspan="5">Reflectance of surface materials</th></tr>
<tr><td rowspan="4">ρ</td><td>Brick wall</td><td>Painted wall</td><td>Floor</td><td>Ceiling</td></tr>
<tr><td>0.17</td><td>0.82</td><td rowspan="3">0.60</td><td rowspan="3">0.27</td></tr>
<tr><td colspan="2">Wall (average)</td></tr>
<tr><td colspan="2">0.37</td></tr>
</table>

4.1.2. Selection of Luminaire Types

Two different luminaires which are available for office environment; LED and fluorescent are selected for the test case. Suspended ceilings are generally used in offices and their size mostly 600x600mm. Because of these reasons, recessed mounted modular luminaires have been selected according to architectural qualities of the space. Luminous flux of luminaire with LED is 3700 lumen while the one with fluorescent is 3780 lumen. Data sheets of selected LED and Fluorescent luminaires is showed in Table 4.2.

Table 4.2. Data sheets of selected LED and Fluorescent luminaires.

	
	
CoreLine/ Recessed mounted/ LED	Centura/ Recessed mounted/ Fluorescent
SM120V LED37S/840 PSU W60L60	TCS160 4xTL-D18W HF C3

4.2. Application of Proposed Model OptimLUM

After preliminary study of OptimLUM, to make the model run flexible at different room dimensions and with different luminaires, calculation formulas were encoded in

Visual Basics (VBA). In this section; before validate the model, these steps developed in Excel, VBA and Evolver will be described.

4.2.1. Excel Spreadsheet Steps

Model was developed through Excel. User needs to contribute some basic information about luminaire type, office dimensions and surfaces to Excel Spreadsheet. These data are divided in two subsections which are office info and luminaire info. Information about office consists of room dimensions (height, width and length) and surface reflectance values (wall, ceiling and floor). Luminaire info includes numeral from database (explained in Chapter 5.), total luminous flux of selected luminaire and how many luminaires will be used in office.

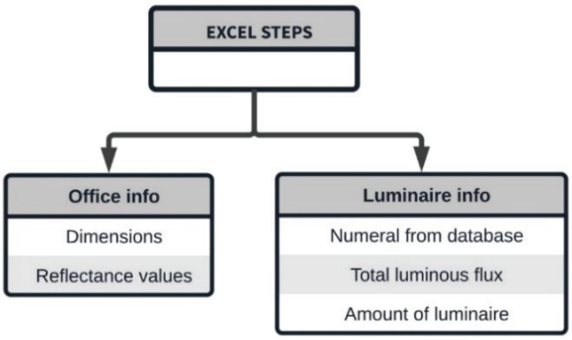


Figure 4.3. Flow chart of Excel spreadsheet steps.

4.2.2. Visual Basics (VBA)

The first step in VBA was to generate grids on the working plane and ceiling to determine calculation points and luminaire location points. Their co-ordinates on x, y and z plane were generated through calculating the arithmetic mean of the room length and width. The grid size of calculation points was set to be 400x600mm. The grid size of luminaire location points was 600x600mm. Such non-aligned grids were used to get the contribution of various distribution angles of the luminaires which result in dissimilar illuminances. Based on these grids, Gamma (γ) and C angles between calculation points and location points of light source were calculated as outputs at this step.

The second step is about basic metric for visual comfort which is illuminance. Calculation of illuminance can be possible through a certain number of mathematical processes related to the behavior of light to get adequate illuminated spaces. These mathematical calculations guide designers to decide lighting sources' layout. Point method is one of them based on illuminance at any point on observed surface (IESNA 2011). With users' data input in spreadsheet and gamma & C angles of two grids, direct and indirect illuminance components are calculated for each calculation point. Total and average illuminance are obtained. Uniformity is another metric that helps to understand differentiation of illuminance values in the whole space. It is the third step; it is calculated according to the formula of MRD.

Furniture was not taken account in calculations. Since mostly their layout can be flexible. Work plane illuminance has the significance in uniformity and average illuminance calculations. So, the model is an abstraction of an empty office geometry.

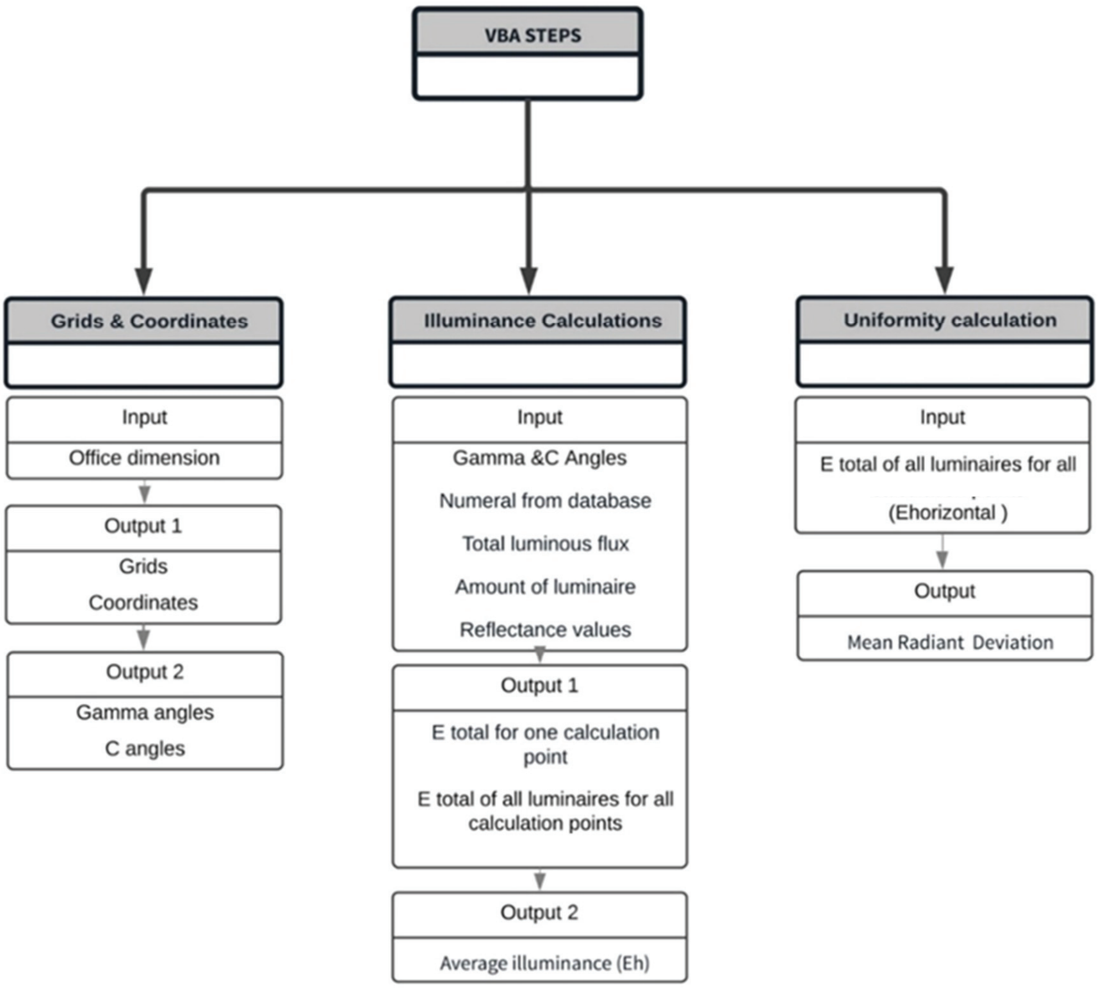


Figure 4.4. Flow chart of VBA steps.

4.2.3. Objective Function and Constraints

Optimization is a progress to find most appropriate solution for a problem having many conceivable solutions. EVOLVER 6 (ADD-INS for Excel) was used as optimizer which is for non-linear optimization problems and the EXCEL spreadsheet application (Palisade Corporation 2013). EVOLVER uses genetic algorithm (GA) which is an optimization method based on Darwinian principles of natural selection and OptQuest Engine which includes metaheuristic, mathematical optimization, and neural network components to get best solutions to decision and planning problems of all types.

The optimization model includes many decision variables based on the objective function, and constraints. So, all possible luminaire location points, illuminance at each calculation point, average illuminance and uniformity (MRD) were calculated and were used as the main input data in the optimization model. Here, the primary objective of the research is to get illuminance uniformity (4.2) closer to zero on the working plane (0.8m) that means minimum deviation between illuminance levels at each calculation point (Ferentinos and Albright 2005). There are two hard constraints which are recommended illuminance for offices between 300-500 lux (CIBSE 2005) (4.3, 4.4). E_{avg} is the average illuminance of working place. E_i is the illuminance level at one calculation point, and E_m is the mean of illuminance at all these points.

Variables are to find location of luminaires:

$$(x_1, \quad y_1), (x_2, \quad y_2), (x_n, \quad y_n)\ldots\ldots$$

Minimize uniformity:

$$MRD = \frac{\sum_{i=1}^{N} |E_i - E_m|}{NI} \tag{4.2}$$

Subject to:

$$E_{avg} \geq 300 \tag{4.3}$$

$$E_{avg} \leq 500 \tag{4.4}$$

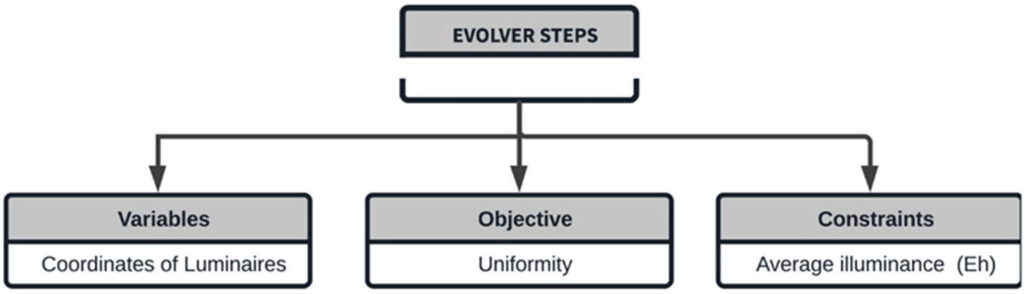


Figure 4.5. Flow chart of optimization progress.

4.3. Validation of OptimLUM

Each light source location is designated with a number starting from the first upper left grid (1) and ending at the last lower right grid (40). Employing these two grids, objective function and constraints together, OptimLUM generated a total of 22359 possible installation scenarios for LED luminaires. 2359 were the best trials among 19626 valid trials. It is also produced 22483 total trials for fluorescent luminaires. The number of best trials was 9691 among 11507 valid trials. The computational times for calculating the optimal solutions were 809s and 814s respectively. OptQuest engine was the optimization engine to get solutions of both luminaire types.

Model estimated two optimum layout scenarios using three LED and fluorescent separately, presenting the minimum deviation in uniformity and satisfying the required average illuminance (Figure 4.6 and Figure 4.7).

Besides layouts obtained from OptimLUM, two alternative ones were offered to validate illuminance calculation of OptimLUM and optimized estimation of OptimLUM comparing illuminance and uniformity results (Figure 4.6 and Figure 4.7). In Alternative I, three luminaires were located linearly and had symmetrical distance from walls. Alternative II includes three luminaires, which were placed arbitrarily in triangle layout (Figure 4.6 and Figure 4.7). One set of these three layouts was analyzed including LEDs, while another set involved fluorescent luminaires.

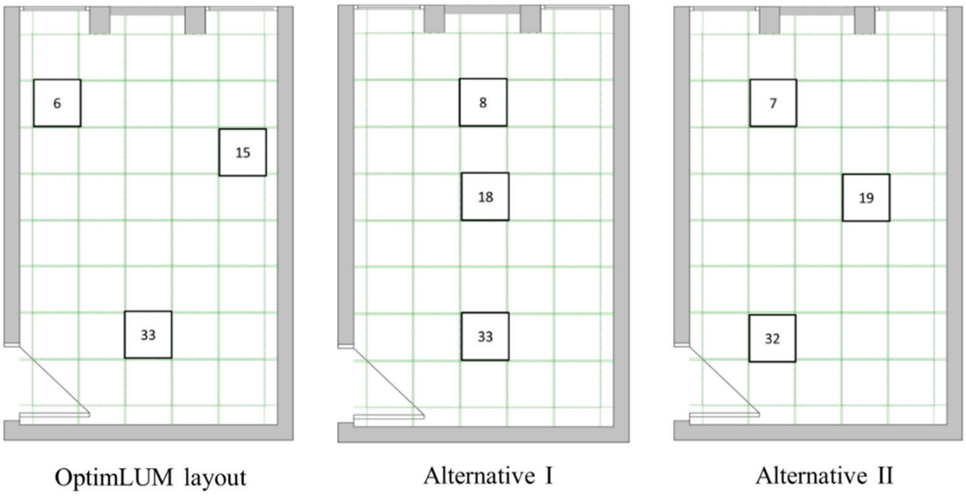


Figure 4.6. OptimLUM layouts, Alternative I and Alternative II for luminaires with LED.

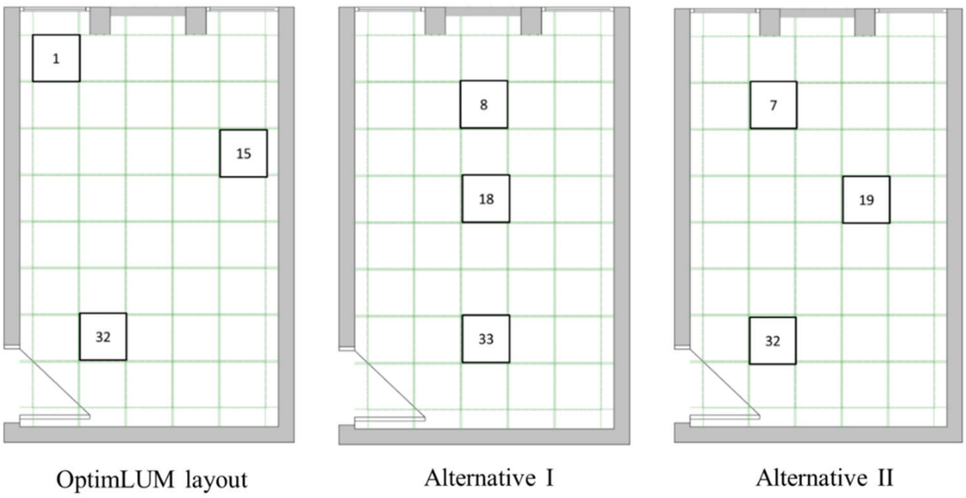


Figure 4.7. OptimLUM layouts, Alternative I and Alternative II for luminaires with fluorescent.

4.3.1. Measurements

In order to evaluate calculation process of OptimLUM and validate estimations of model about luminaire layouts for offices, artificial lighting measurements were taken in an actual office for different luminaire types. A digital light meter (Lutron LX-1108) is used to obtain illuminance values on reference points (Figure 4.8). Calculation grid coordinates defined by OptimLUM were used as illuminance measurement points in test case (Figure 4.9). Blinds of the windows are blocked the sunlight. Thus, only illuminance from artificial lighting can be measured without daylight effect.

Figure 4.8. Digital light meter (Lutron LX-1108).

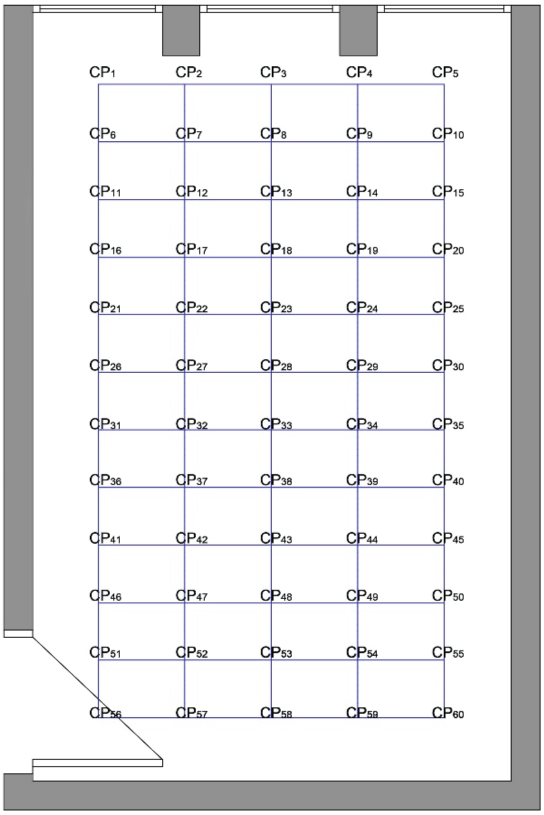


Figure 4.9. Calculation points in test case for validation.

For installation of luminaires, firstly, the steel ropes are placed in parallel with the walls. Then the luminaires are placed on the ropes. Luminaires are shifted on the steel ropes according to OptimLUM layouts, Alternative I and Alternative II (Figure 4.10 and Figure 4.11).

Figure 4.10. Installation of luminaires with fluorescent.

Figure 4.11. Installation of luminaires with LED.

In addition to triple layouts mentioned above, to find the contribution of each luminaire to each measurement point, new layouts including single and double luminaires were determined to validate the illuminance calculation process of OptimLUM. During the measurement step, illuminance values of single and double configurations of luminaires were measured on work plane (0.8m height) by switching on while the other luminaires are switched off in the actual test case. (Table 4.3)

Table 4.3. Number of scenarios.

		OptimLUM	Alternative I	Alternative II
LED	single	3	2	2
	double	3	3	2
	triple	1	1	1
Fluorescent	single	2	2	2
	double	3	3	3
	triple	1	1	1
TOTAL	36			

4.3.2. Simulation (DIALux)

After the measurement process, a total of 36 layouts including triple, double and single configurations were simulated in DIALux, Calculation grid coordinates defined by OptimLUM were used as calculation points for simulation. Illuminance values of each points are calculated in DIALux. To observe differentiation of illuminance distributions between layouts, output graphs of OptimLUM estimation, Alternative I and Alternative II are obtained from DIALux.

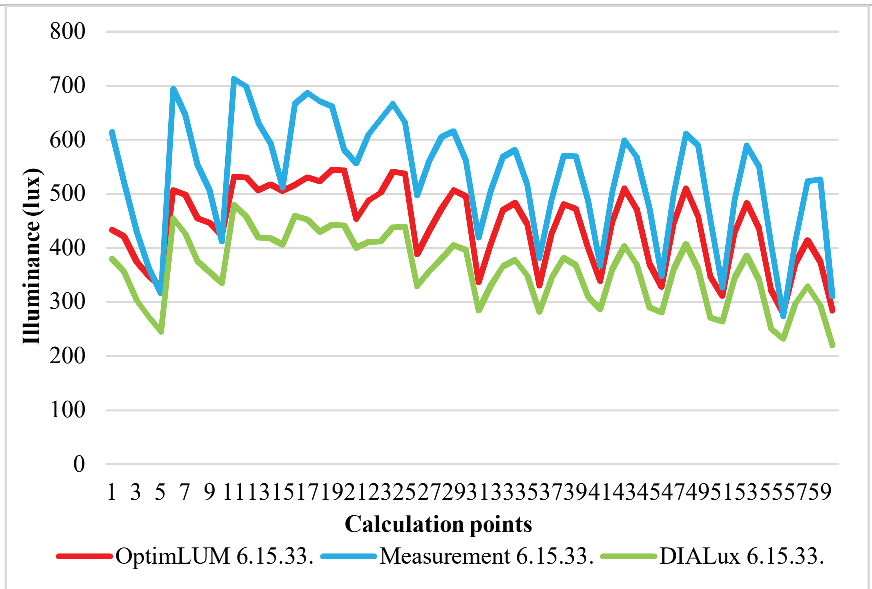
4.3.3. Comparison of Measurements, Simulation and OptimLUM

Illuminance measurements and DIALux simulations aimed to test the performance illuminance calculation method of optimization model and to validate layout estimation of OptimLUM by comparing illuminance and uniformity. This process includes two phases. Firstly, illuminance calculation method of the model was evaluated statistically by comparing measurements, simulation and OptimLUM illuminance outputs. Then, E_{avg} and two uniformity results of OptimLUM estimation layout, Alternative I and II for Luminaires with LED and fluorescent are compared numerically and supported with the output graphs obtained from DIALux,

4.3.3.1. Statistical Evaluation of Measurements, Simulation and OptimLUM Calculation

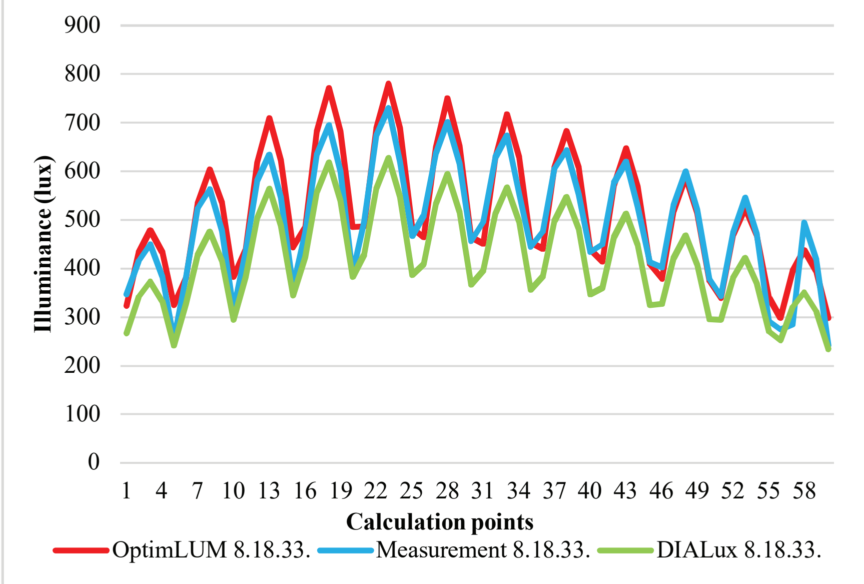
Illuminance distributions of all scenarios were compared by line charts. All analyses were repeated. The obtained results were explained in the Appendix A by tables and graphs. It was observed that OptimLUM outputs are closer to the actual measurements when compared with DIALux outputs. When we compare OptimLUM layout and Alternative I findings for LED in Table 4.4 and Table 4.5 regarding minimum, maximum, average values and standard deviations, OptimLUM outputs were very slightly higher than DIALux outputs while both of them remained lower than the measurement values. A few deviations between fluctuation lines between OptimLUM, DIALux and measurement values in OptimLUM layout were observed in Table 4.4, when we compared it with Alternative I layout in Table 4.5. Yet, illuminance values calculated by OptimLUM fits very well with the measurement values regarding the overall results for luminaires with fluorescent lamps. Similar results are obtained from repeated analyses (Appendix A).

Table 4.4. Distributions of illuminance values in OptimLUM layout for LED luminaire.



LED MODEL (6.15.33.)				
	Min	**Max**	**Avg**	**SD**
OptimLUM	279.92	545.22	441.72	73.17
Measurements	273.90	713.00	532.55	108.25
DIALux	220.00	480.00	360.63	64.47

Table 4.5. Distributions of illuminance values Alternative I layout for LED luminaire.



LED ALTERNATIVE I (8.18.33.)				
	Min	**Max**	**Avg**	**SD**
OptimLUM	297.67	780.40	518.10	128.26
Measurements	241.40	730.00	495.63	120.87
DIALux	234.00	628.00	418.27	101.28

Scatter diagrams were used to validate the OptimLUM model by comparing OptimLUM values and illuminance measurements. Excel calculated the coefficient of determination (R^2) and the linear regression equation. The model performance is highly accurate in calculating illuminance values with R^2 of 86-99 % (Table 4.6,

Table 4.7and Table 4.8). Similar results are obtained from repeated analyses (Appendix-A).The highest coefficient of determination which is 99% is observed in single luminaire configuration calculated by OptimLUM (Table 4.6) Root mean square error (RMSE) which is an indicator to show differences between outputs is calculated by given formula;

$$E = \sqrt{\frac{\sum_{t=1}^{N} (o_{1,t} - m_{1,t})^2}{N}} \quad (4.5)$$

Where (E) is the RMS error, o is the illuminance output of OptimLUM, and m is the measured illuminance for all calculation points, N is the number of calculation points. These error values change between 17.88 and 102.90 in general. The least errors are similarly obtained from single luminaire configuration by OptimLUM with 17.88 and 18.40 of RMSE. Although model outputs fit the measurements with the highest R^2, the single LED configuration performs better with the minimum error rate. Normalized root mean square error (NRMSE) is another statistical error indicator to evaluate reliability of the outputs can be calculated with Eq. (4.6). o_{max} is the maximum illuminance output of OptimLUM and o_{min} is the minimum illuminance output of OptimLUM. Similar and lower NRMSE values (0.04-0.08) for all configurations indicate the consistency of the OptimLUM (Table 4.6, Table 4.7 and Table 4.8).

$$NRMSE = \frac{\sqrt{\frac{\sum_{t=1}^{N}(o_{1,t}-m_{1,t})^2}{N}}}{o_{max}-o_{min}} \quad (4.6)$$

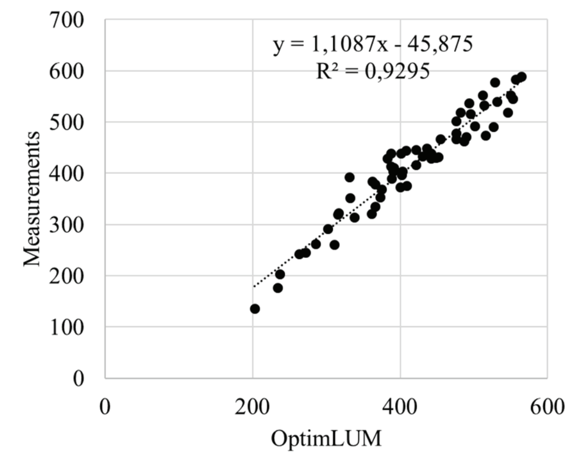
The CV (coefficient of variation of root mean square error) is one of statistical indices to determine the similarity of the optimization model calculated by given formula (4.7) where $\bar{m}$ is the sample mean of illuminance measurements. As the CV is closer to 0%, OptimLUM illuminance values are closer to illuminance measurements. CV for all scenarios between 4-12 % show the reliability of the model (Table 4.6, Table 4.7 and Table 4.8).

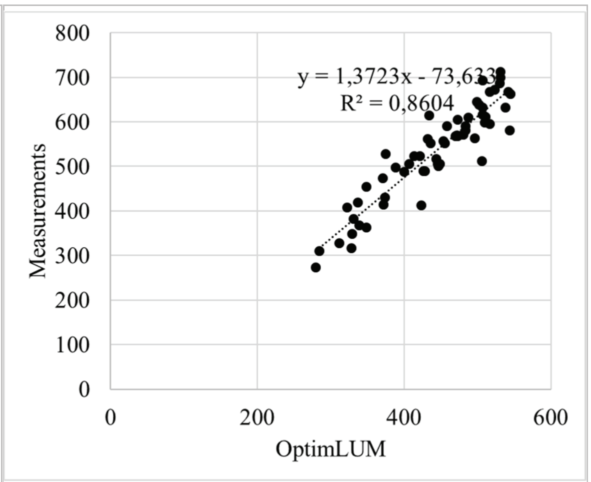
$$CV = \frac{RMSE}{\bar{m}} * 100 \quad (4.7)$$

4.3.3.2. Validation of Optimization Process

Model aimed to optimize the uniform illumination with an average illuminance based on standards (CIBSE 2005). Comparison between alternative layouts and OptimLUM proposed layout shows that the evolved one by OptimLUM achieved an average illuminance closer to the standards (300-500 lux), while Alternative I for luminaire with LED did not. In addition, regarding uniformity, OptimLUM layout provided better uniformity with 0.13 of MRD for both types of luminaires. Since this shows us the minimum deviation which is close to zero. Additionally, U (E_{min}/E_{avg}) is calculated as 0.63 which is the highest the among others and closest to the reference uniformity value of 0.8 (CIBSE 2005) (Table 4.9).

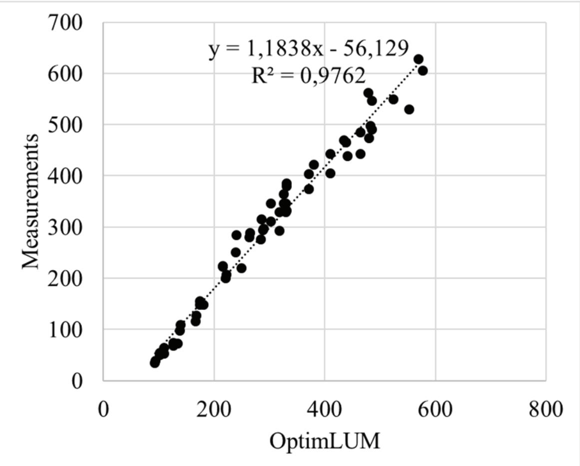
Table 4.6. Statistical analysis in Alternative II layout of Fluorescent and OptimLUM layout of LED.

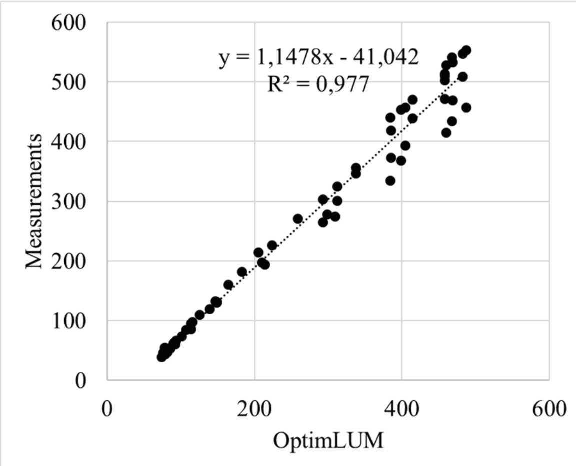




FLUORESCENT ALTERNATIVE II (7.19.32.)		LED MODEL (6.15.33.)	
RMSE	25.95	RMSE	102.90
NRMSE	0.08	NRMSE	0.04
CV	0.07	CV	0.04

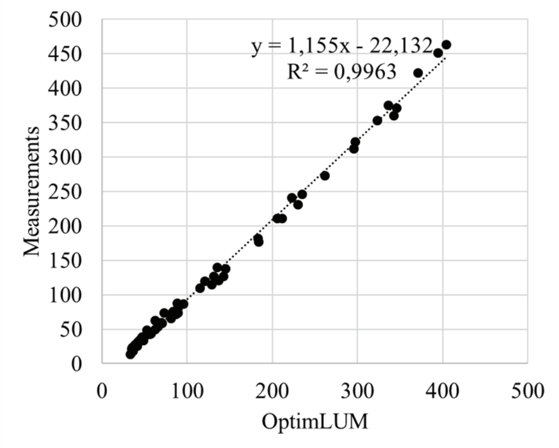
Table 4.7. Statistical analysis of double luminaires configuration in Alternative I layout of Fluorescent and OptimLUM layout of LED.

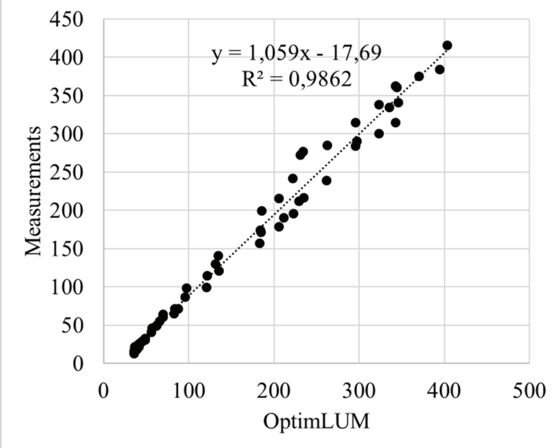




FLUORESCENT ALTERNATIVE I (8.18.)		LED MODEL (6.15.)	
RMSE	35.70	RMSE	34.54
NRMSE	0.07	NRMSE	0.08
CV	0.12	CV	0.06

Table 4.8. Statistical analysis of single luminaires configuration in Alternative I layout of Fluorescent and OptimLUM layout of LED.





LED MODEL (6.)		**LED ALTERNATIVE I (8.)**	
RMSE	18.40	RMSE	17.88
NRMSE	0.05	NRMSE	0.05
CV	0.08	CV	0.08

Table 4.9. E_{avg} and two Uniformity results of OptimLUM estimation layout, Alternative I and II for Luminaires with LED and fluorescent.

		OptimLUM	**Alternative I**	**Alternative II**
LED	$\mathbf{E_{avg}}$	441.72 lux	518.09 lux	491.21 lux
	U (MRD)	0.13	0.21	0.17
	U ($\mathbf{E_{min}/ E_{avg}}$)	0.63	0.57	0.45
Fluorescent	$\mathbf{E_{avg}}$	327.83 lux	407.24 lux	387.89 lux
	U (MRD)	0.13	0.21	0.17
	U ($\mathbf{E_{min}/ E_{avg}}$)	0.52	0.58	0.49

Supporting the analyzes mentioned above, based on the output graphs obtained from DIALux, OptimLUM estimation layout for luminaires with LED provided approximately 300-400 lux, uniform illuminance distributions in a large part of the room. In Alternative I layout, illuminance with 560 lux is observed in the small and middle area of the office while the values decrease below 320 lux at the corners. Likely Alternative I, Alternatıve II provided 480 lux in the middle. Although the middle area is bigger than Alternative I, its uniformity is poor regarding OptimLUM estimation because of the illuminance differences between middle and the corners (Figure 4.12).

Similar distributions mentioned above, OptimLUM estimation layout for luminaires with fluorescent provided better uniform illuminance (300-400 lux) on the large part of the work plane. Alternative I and Alternative II for luminaires with fluorescent illuminated the middle area of the room with the values over 500 lux. Two different alternative layouts do not meet the specific requirements, established by the standards (Figure 4.13).

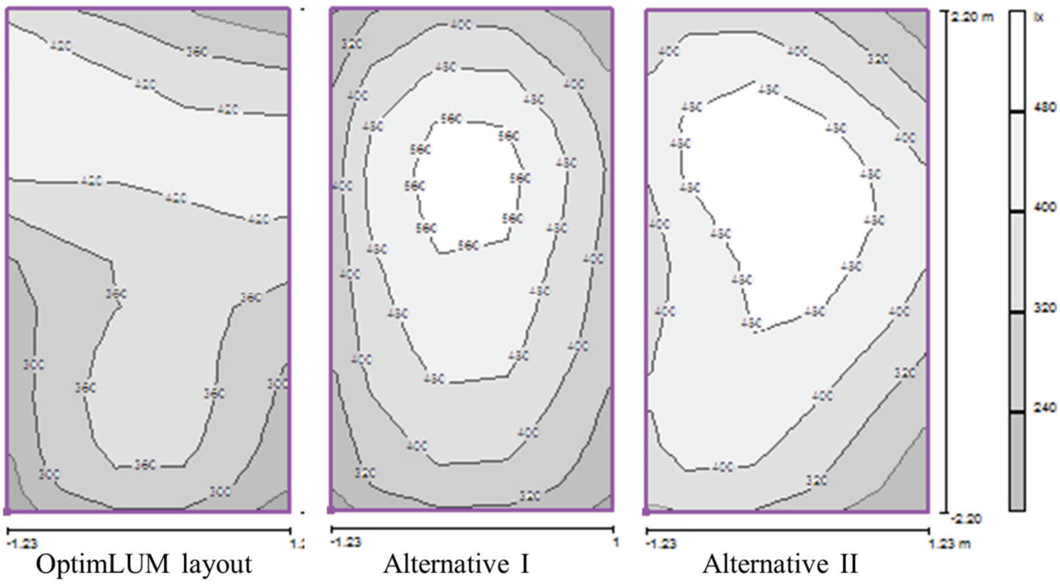


Figure 4.12. Illuminance distribution of OptimLUM estimation, Alternative I and Alternative II for luminaires with LED (DIALux).

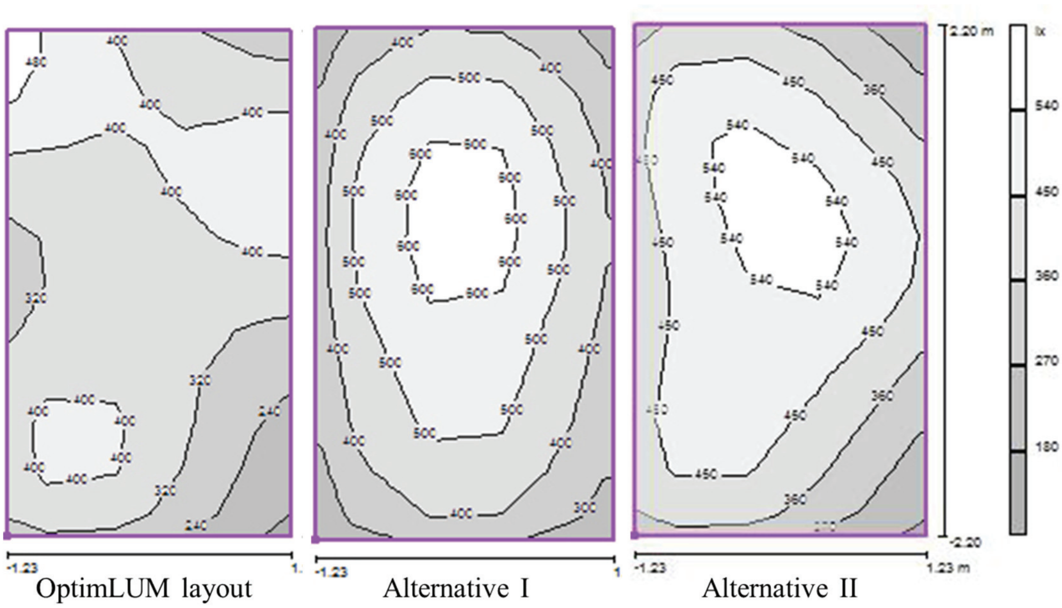


Figure 4.13. Illuminance distribution of OptimLUM estimation, Alternative I and Alternative II for luminaires with fluorescent (DIALux).

In an actual test case, this new proposed tool was studied by illuminance measurements and simulations. Two different types of luminaires (LED and fluorescent) were used for case study. Apart from OptimLUM layout results for two luminaires, two alternative layouts including single and double luminaire configurations were determined. Based on illuminance distributions for all scenarios, OptimLUM outputs are closer to the actual measurements when compared with DIALux outputs. Model outputs present a high accuracy with the illuminance measurements.

CHAPTER 5

MODEL APPLICATION

After validation of OptimLUM, development of the model will be explained in this chapter. Included parameters and constraints will be clarified. Luminaire database for OptimLUM users and selected room sizes to generate luminaire layout results will be presented. As the results are sufficient for progress of OptimLUM, it is now necessary to produce energy efficient luminaire layout solutions. These layouts should also be integrated with daylight to display number of luminaires during the daytime and for darkest conditions.

5.1. Progress of OptimLUM

The initial purpose of OptimLUM is to estimate most accurate locations of light sources according to average illuminance on work plane and maximum uniformity proposing an optimization model. As mentioned before, for validation of the model, a small cellular office was selected to measure illuminance provided by different luminaire types and optimization model according to these measurements. Model results, measurements and DIALux results were considered together to validate model calculation. Comparison of the results were satisfying. After validating of the model, it is decided to add some constraints about walls to avoid excessive luminance and prevent glare on vertical surfaces.

The other subjective is uniformity formula. Different uniformity formulas are used in lighting researches. The ratio of minimum illuminance to average illuminance on a surfaces is commonly used. Other formula is mean relative deviation (MRD) which is selected uniformity formula for this model. Two formulas were used separately for OptimLUM to observe differences of their results.

A luminaire database for offices, which includes luminous flux and photometric data of luminaires from various manufacturers was generated for OptimLUM users to select luminaire type easily.

Finally, to represent energy efficient luminaire layouts for different volumes; small, medium and large space are defined.

5.1.1. Selection of Input Parameters and Constraints

After concluding the validating steps of the model, OptimLUM is developed based on arising doubts about excessive luminance and glare on vertical surfaces. Firstly, the model is upgraded to calculate illuminance on the walls. Illuminance grids which is similar to work plane was constructed for walls (Figure 5.1). Model generates their co-ordinates on x, y and z according to point of 0, 0, and 0 on left and bottom side of the room. C and gamma angles which are resulting angles on horizontal and vertical surface between location points of light source and calculation points on walls were calculated similarly to work plane surface. Vertical surface illuminance formula was set based on;

$$E_v = \frac{\left(\frac{\Phi}{1000}\right) * I_{rel} * \cos^2 \alpha * \sin \alpha}{h^2} \quad (5.1)$$

Luminance of walls was calculated by the given formula above;

$$L = \frac{E_v * \rho}{\pi} \quad (5.2)$$

E_v = *illuminances on vertical surfaces*

ρ = *reflectance of surface*

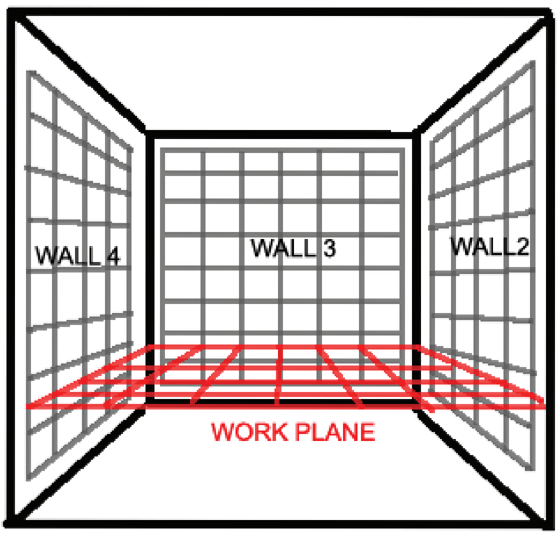


Figure 5.1. Grids on walls and work plane.

Illuminance of walls is related with illuminance of horizontal surface throughout the whole office to provide visual satisfaction for users. Code for lighting in UK (CIBSE) recommends for the ratio between the average illuminance on wall to average illuminance on horizontal working plane to be between the ranges 0.5-0.8 (CIBSE/SLL 2002). Model uses this ratio as a constraint for four walls.

$$0.5 \leq \frac{E_{avg,wall1}}{E_{avg,hor}} \leq 0.8 \tag{5.3}$$

$$0.5 \leq \frac{E_{avg,wall2}}{E_{avg,hor}} \leq 0.8 \tag{5.4}$$

$$0.5 \leq \frac{E_{avg,wall3}}{E_{avg,hor}} \leq 0.8 \tag{5.5}$$

$$0.5 \leq \frac{E_{avg,wall4}}{E_{avg,hor}} \leq 0.8 \tag{5.6}$$

Also there is a recommendation about luminance for walls of offices. Luminance of walls should be between 50-150 cd/m^2 (CIBSE/SLL 2002). Model also uses these values as constraints for four walls.

$$50 \leq L_{avg,wall1} \leq 150 \tag{5.7}$$

$$50 \leq L_{avg,wall2} \leq 150 \tag{5.8}$$

$$50 \leq L_{avg,wall3} \leq 150 \tag{5.9}$$

$$50 \leq L_{avg,wall4} \leq 150 \tag{5.10}$$

Two different uniformity formulas are used in lighting evaluation researches. The ratio of minimum illuminance to average illuminance on a surfaces is commonly used; E_{min}/E_{avg}. It is expected to be close to 1 and it is recommended to be higher than 0.7 (CIBSE/SLL 2002) (IESNA 2011). Because of this reason, optimization goal of this research is to be maximizing this value.

$$U = \frac{E_{min}}{E_{avg}} \tag{5.11}$$

Other formula is mean relative deviation (MRD) that is used to calculate relative deviation of illuminance level at the point from average level of whole space. It should be close to 0 and it is minimized in this research.

$$MRD = \frac{\sum_{i=1}^{N} |E_i - E_m|}{NI} \tag{5.12}$$

Two formulas are used separately for OptimLUM to observe differences of their results. Constraints about horizontal illuminance, vertical illuminance ratios and luminance values on walls are same for both evaluations.

Firstly, model is run for selected office with three luminaires with fluorescent. Due to low reflectance value of walls, luminance cannot get value over 50. According to constraints about the ratio between horizontal (work plane) and vertical surfaces (walls) and uniformity formulas there are some results.

Table 5.1. Room and fluorescent luminaire information to compare different uniformity formulas for current conditions.

LAMP	**F_{total}**	**Luminaire #**	**# of L.p.**
	3780lm	2	40
DIMENSIONS	**Height**	**Width**	**Length**
	2.9 m	3.32 m	5.33m
SURFACES	**r_{wall}**	**r_{ceil}**	**r_{floor}**
	0.37	0.27	0.6
r_{avg}	0.39		
E_{ref}	29.09 lux		

When maximizing uniformity formula (E_{min}/E_{avg}), three luminaires are located on 6, 15, 33 points as seen on Table 5.2 . Average illuminance on working plane is 328.526 lux and uniformity is 0.72 Uniformity value is between recommended range (>0.7).

While the objective is minimizing the uniformity formula (MRD), three luminaires locations resulted on 9, 26, 40 points as seen on Table 5.3. E avg is 328.526 lux and uniformity is 0.12. Two different uniformity formula give similar results for $E_{avg;hor}$ and illuminance ratios between walls and work plane.

Table 5.2. Results of fluorescent luminaires on selected office, based on maximizing uniformity formula for current conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	6
Luminaire 2	15
Luminaire 3	38
$E_{avg;hor}$	**328.53 lux**
Uniformity	**0.72**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.77
E_{wall2}/E_{work}	0.75
E_{wall3}/E_{work}	0.55
E_{wall4}/E_{work}	0.72

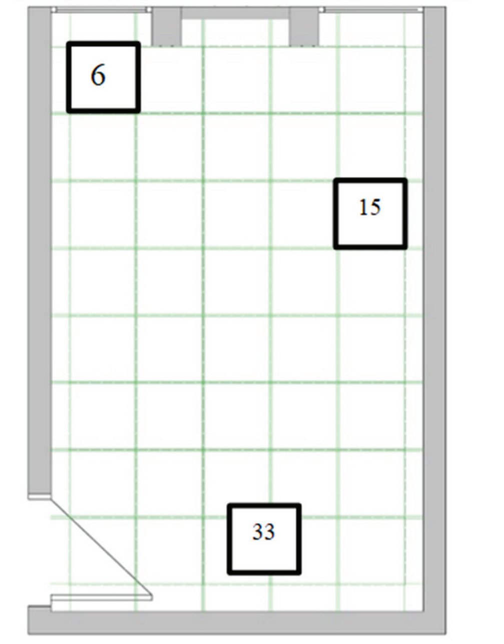
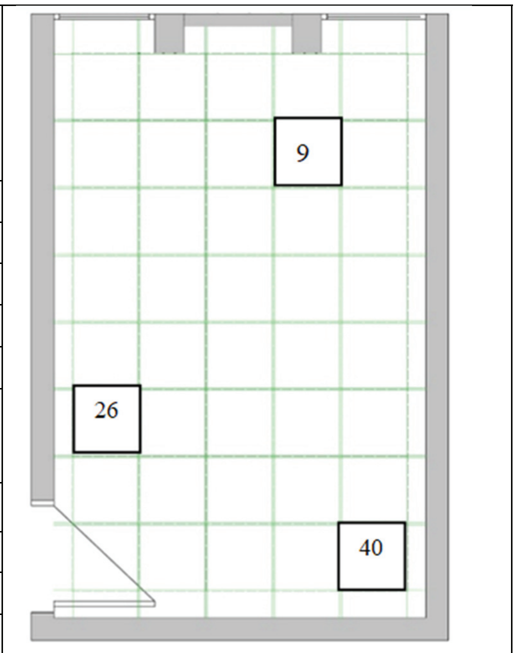


Table 5.3. Results of fluorescent luminaires on selected office, based on minimizing uniformity formula (MRD) for current conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	26
Luminaire 2	40
Luminaire 3	9
$E_{avg;hor}$	**327.83 lux**
Uniformity	**0.12**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.75
E_{wall2}/E_{work}	0.74
E_{wall3}/E_{work}	0.51
E_{wall4}/E_{work}	0.72



Secondly, model is run for selected office with three LED luminaires (Table 5.4). Similarly model with fluorescent luminaires, due to low reflectance value of walls, luminance cannot get value over 50. According to constraints about the ratio between horizontal and vertical surfaces and uniformity formula, results is presented below. Maximizing uniformity formula (E_{min}/E_{avg}) with luminaires with LED concludes the layout for three luminaires by setting on 6, 14, 38 points as seen on Table 5.5. Average illuminance on working plane is 438.20 lux and uniformity is 0.64. Uniformity value is under recommended range (>0.7) but it is very close. Minimizing uniformity formula (MRD) located three luminaires on 4, 21, 40 points as seen on Table 5.6. Average illuminance on working plane is 387.354 lux and uniformity is 0.15. In contradistinction to other formula results, illuminance ratios for four walls have closer values to each other.

Table 5.4. Room and LED luminaire information to compare different uniformity formulas for current conditions.

LAMP	**F_{total}**	**Luminaire #**	**# of L.p.**
	3700lm	1	40
DIMENSIONS	**Height**	**Width**	**Length**
	2.9 m	3.32 m	5.33m
SURFACES	**r_{wall}**	**r_{ceil}**	**r_{floor}**
	0.37	0.27	0.6
r_{avg}	0.39		
E_{ref}	29.09 lux		

Table 5.5. Results of LED luminaires on selected office, based on maximizing uniformity formula for current conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	14
Luminaire 2	38
Luminaire 3	6
$E_{avg;hor}$	**438.20 lux**
Uniformity	**0.64**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.71
E_{wall2}/E_{work}	0.51
E_{wall3}/E_{work}	0.52
E_{wall4}/E_{work}	0.68

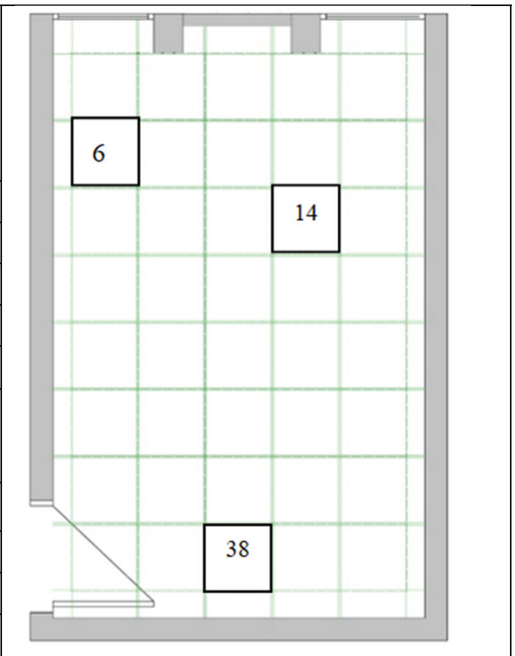
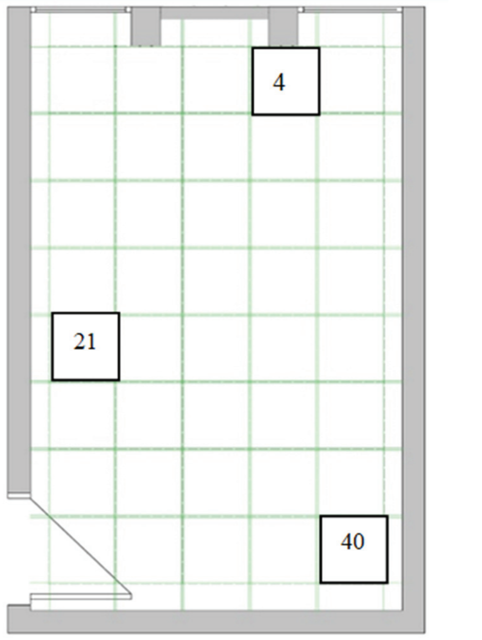


Table 5.6. Results of LED luminaires on selected office, based on minimizing uniformity formula for current conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	21
Luminaire 2	4
Luminaire 3	40
$E_{avg;hor}$	**387.35 lux**
Uniformity	**0.15**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.71
E_{wall2}/E_{work}	0.73
E_{wall3}/E_{work}	0.79
E_{wall4}/E_{work}	0.74



According to Lighting Manual (Philips Lighting B.V. 1993), there are some recommendations about surface reflectance values. Ceiling should be 0.7 or above, walls should be between 0.5-0.7 and floors between 0.1-0.3. Reflectance values on OptimLUM are reorganized based on this information. To analyze the effect of surface features on model results, rwall was changed as 0.6, r_{ceil} is 0.7 and r_{floor} is 0.2. Consequently, r_{avg} and $E_{reflected}$ were changed also (Table 5.7).

By minimizing MRD formula, three luminaires positioned on 1, 19, 39 points as seen on Table 5.8. Average illuminance on working plane is 400.36 lux and uniformity is 0.14. Average luminance values on walls are between 50 and 150 cd/m2 due to constraint for the model. But there are some values that are higher than expected. These calculation points are located very close to luminaires. Due to luminaire located on 1, these higher values can be observed on wall 3 and 4 Table 5.9.

As a result of maximizing uniformity formula, three luminaires located on 2, 22, 40 points as seen on Table 5.10. Average illuminance on working plane is 400.36 lux similar to other uniformity formula and uniformity is 0.62. Illuminance ratios on opposing walls are closer. Due to luminaire located on 2 and 40, there are some results higher than expected on wall 1, 3 and 4. Similarly, MRD formula results, these calculation points are located very close to luminaires (Table 5.11).

Table 5.7. Room and fluorescent luminaire information to compare different uniformity formulas for recommended conditions.

LAMP	**F_{total}**	**Luminaire #**	**# of Lum**
	3780lm	2	40
DIMENSIONS	**Height**	**Width**	**Length**
	2.9 m	3.32 m	5.33m
SURFACES	**r_{wall}**	**r_{ceil}**	**r_{floor}**
	0.6	0.7	0.2
r_{avg}	0.54		
E_{ref}	51.43 lux		

Table 5.8. Results of fluorescent luminaires on selected office based on minimizing uniformity formula and surface reflectance values for recommended conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	19
Luminaire 2	39
Luminaire 3	1
$E_{avg;Hor}$	**400.36 lux**
Uniformity	**0.15**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.80
E_{wall2}/E_{work}	0.68
E_{wall3}/E_{work}	0.75
E_{wall4}/E_{work}	0.69
LUMINANCE	
$L_{wall1;avg}$	60.94 cd/m^2
$L_{wall2;avg}$	51.63 cd/m^2
$L_{wall3;avg}$	57.06 cd/m^2
$L_{wall4;avg}$	52.99 cd/m^2

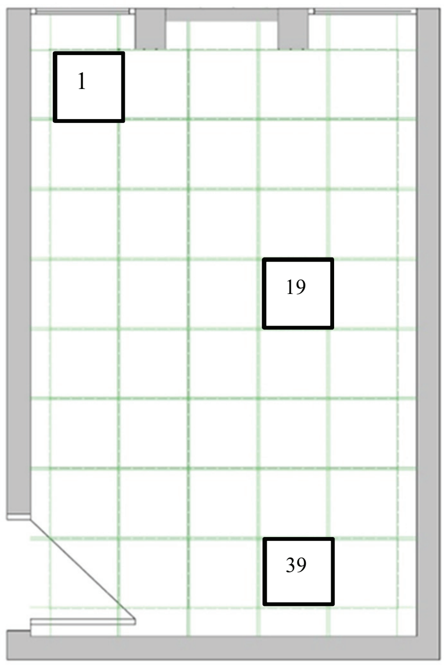


Table 5.9. Luminance and illuminance values on walls results (fluorescent luminaires on selected office) based on minimizing uniformity formula for recommended conditions.

luminance	wall1	illuminance
29.51	1	154.53
29.66	2	155.31
60.38	3	316.16
177.77	4	930.79
60.38	5	316.16
31.33	6	164.04
48.84	7	255.71
98.33	8	514.85
127.32	9	666.65
98.33	10	514.84
39.96	11	209.25
57.93	12	303.34
75.16	13	393.53
75.80	14	396.87
75.16	15	393.53
44.39	16	232.40
54.33	17	284.47
58.62	18	306.92
55.90	19	292.71
58.61	20	306.90
44.93	21	235.24
50.14	22	262.56
50.48	23	264.29
47.56	24	249.01
50.41	25	263.92
44.61	26	233.58
46.95	27	245.83
46.09	28	241.31
43.74	29	229.00
45.71	30	239.36

luminance	wall2	illuminance
34.50	1	180.62
30.69	2	160.70
29.62	3	155.07
30.69	4	160.71
34.50	5	180.63
30.68	6	160.63
29.55	7	154.75
29.51	8	154.50
71.31	9	373.38
56.79	10	297.33
43.06	11	225.46
56.79	12	297.35
71.32	13	373.42
55.80	14	292.18
36.30	15	190.05
30.52	16	159.78
68.91	17	360.83
67.51	18	353.47
64.51	19	337.80
67.52	20	353.55
69.06	21	361.62
61.85	22	323.87
47.67	23	249.58
36.43	24	190.77
60.89	25	318.80
65.01	26	340.38
66.17	27	346.48
65.39	28	342.37
62.16	29	325.47
58.00	30	303.71
50.92	31	266.60
43.39	32	227.16
54.05	33	283.02
58.42	34	305.87
61.19	35	320.37
59.60	36	312.09
56.66	37	296.67
54.14	38	283.48
51.40	39	269.15
46.35	40	242.66
48.91	41	256.12
52.48	42	274.79
54.59	43	285.85
54.16	44	283.61
52.13	45	272.95
51.09	46	267.52
49.46	47	258.98
46.54	48	243.70

luminance	wall3	illuminance
177.77	1	930.79
60.38	2	316.17
29.67	3	155.35
29.52	4	154.58
29.50	5	154.47
127.32	6	666.64
98.35	7	514.95
48.88	8	255.96
31.38	9	164.33
29.60	10	154.97
75.79	11	396.86
76.20	12	398.98
60.62	13	317.42
43.06	14	225.44
34.83	15	182.36
55.89	16	292.66
60.66	17	317.60
59.35	18	310.76
50.48	19	264.31
42.31	20	221.52
47.55	21	248.96
52.55	22	275.13
55.20	23	289.02
51.21	24	268.11
45.98	25	240.75
43.73	26	228.95
47.60	27	249.22
50.65	28	265.19
49.64	29	259.92
46.31	30	242.48

luminance	wall4	illuminance
29.50	1	154.46
29.50	2	154.46
29.50	3	154.46
29.51	4	154.51
29.53	5	154.62
29.71	6	155.57
77.57	7	406.15
261.28	8	1368.05
29.83	9	156.20
29.57	10	154.85
29.59	11	154.93
29.63	12	155.12
31.71	13	166.06
52.12	14	272.89
107.75	15	564.20
131.03	16	686.05
33.72	17	176.55
34.06	18	178.35
34.43	19	180.26
37.02	20	193.84
44.34	21	232.15
63.34	22	331.63
77.94	23	408.11
72.45	24	379.33
39.76	25	208.20
40.58	26	212.46
42.10	27	220.42
46.83	28	245.18
53.75	29	281.44
61.48	30	321.88
61.29	31	320.91
53.33	32	279.24
42.63	33	223.22
45.44	34	237.93
48.20	35	252.39
51.57	36	270.01
55.03	37	288.12
57.08	38	298.89
52.98	39	277.43
46.46	40	243.25
44.13	41	231.05
47.04	42	246.31
49.32	43	258.25
52.16	44	273.10
53.40	45	279.60
53.02	46	277.61
48.24	47	252.57
43.28	48	226.61

Same reflectance values were applied with LED luminaire with luminous flux; 3700. According to results of maximizing uniformity formula, three luminaires positioned on 1, 15, 38 points as seen on Table 5.13. Average illuminance on working plane is 484.25 lux and uniformity is 0.71. Illuminance result is satisfying and uniformity value is between recommended ranges. Due to luminaire located on 1 and 15, there are some results higher than expected on wall 3 and 4. These calculation points are also located very close to luminaires like fluorescent results (Table 5.14).

Table 5.10. Results of fluorescent luminaires on selected office, based on maximizing uniformity formula and surface reflectance values for recommended conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	22
Luminaire 2	40
Luminaire 3	2
$E_{avg;Hor}$	**400.36 lux**
Uniformity	**0.63**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.75
E_{wall2}/E_{work}	0.69
E_{wall3}/E_{work}	0.80
E_{wall4}/E_{work}	0.68
LUMINANCE	
$L_{wall1;avg}$	57.06 cd/m^2
$L_{wall2;avg}$	52.99 cd/m^2
$L_{wall3;avg}$	60.94 cd/m^2
$L_{wall4;avg}$	51.62 cd/m^2

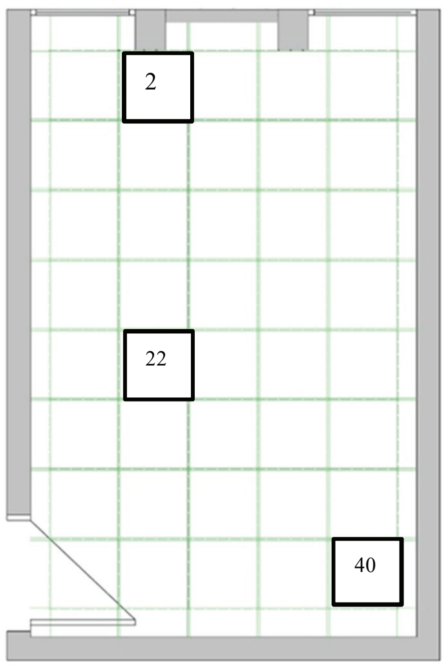


Table 5.11. Luminance and illuminance values on walls results (fluorescent luminaires on selected office) based on maximizing uniformity formula for recommended conditions.

luminance	wall1	illuminance
29.50	1	154.47
29.52	2	154.58
29.67	3	155.35
60.38	4	316.17
177.77	5	930.79
29.60	6	154.97
31.38	7	164.33
48.88	8	255.96
98.35	9	514.95
127.32	10	666.64
34.83	11	182.36
43.06	12	225.44
60.62	13	317.42
76.20	14	398.98
75.79	15	396.86
42.31	16	221.52
50.48	17	264.31
59.35	18	310.76
60.66	19	317.60
55.89	20	292.66
45.98	21	240.75
51.21	22	268.11
55.20	23	289.02
52.55	24	275.13
47.55	25	248.96
46.31	26	242.48
49.64	27	259.92
50.65	28	265.19
47.60	29	249.22
43.73	30	228.95

luminance	wall2	illuminance
261.28	1	1368.05
77.57	2	406.15
29.71	3	155.57
29.53	4	154.62
29.51	5	154.51
29.50	6	154.46
29.50	7	154.46
29.50	8	154.46
131.03	9	686.05
107.75	10	564.20
52.12	11	272.89
31.71	12	166.06
29.63	13	155.12
29.59	14	154.93
29.57	15	154.85
29.83	16	156.20
72.45	17	379.33
77.94	18	408.11
63.34	19	331.63
44.34	20	232.15
37.02	21	193.84
34.43	22	180.26
34.06	23	178.35
33.72	24	176.55
53.33	25	279.24
61.29	26	320.91
61.48	27	321.88
53.75	28	281.44
46.83	29	245.18
42.10	30	220.42
40.58	31	212.46
39.76	32	208.20
46.46	33	243.25
52.98	34	277.43
57.08	35	298.89
55.03	36	288.12
51.57	37	270.01
48.20	38	252.39
45.44	39	237.93
42.63	40	223.22
43.28	41	226.61
48.24	42	252.57
53.02	43	277.61
53.40	44	279.60
52.16	45	273.10
49.32	46	258.25
47.04	47	246.31
44.13	48	231.05

luminance	wall3	illuminance
60.38	1	316.16
177.77	2	930.79
60.38	3	316.16
29.66	4	155.31
29.51	5	154.53
98.33	6	514.84
127.32	7	666.65
98.33	8	514.85
48.84	9	255.71
31.33	10	164.04
75.16	11	393.53
75.80	12	396.87
75.16	13	393.53
57.93	14	303.34
39.96	15	209.25
58.61	16	306.90
55.90	17	292.71
58.62	18	306.92
54.33	19	284.47
44.39	20	232.40
50.41	21	263.92
47.56	22	249.01
50.48	23	264.29
50.14	24	262.56
44.93	25	235.24
45.71	26	239.36
43.74	27	229.00
46.09	28	241.31
46.95	29	245.83
44.61	30	233.58

luminance	wall4	illuminance
29.51	1	154.50
29.55	2	154.75
30.68	3	160.63
34.50	4	180.63
30.69	5	160.71
29.62	6	155.07
30.69	7	160.70
34.50	8	180.62
30.52	9	159.78
36.30	10	190.05
55.80	11	292.18
71.32	12	373.42
56.79	13	297.35
43.06	14	225.46
56.79	15	297.33
71.31	16	373.38
36.43	17	190.77
47.67	18	249.58
61.85	19	323.87
69.06	20	361.62
67.52	21	353.55
64.51	22	337.80
67.51	23	353.47
68.91	24	360.83
43.39	25	227.16
50.92	26	266.60
58.00	27	303.71
62.16	28	325.47
65.39	29	342.37
66.17	30	346.48
65.01	31	340.38
60.89	32	318.80
46.35	33	242.66
51.40	34	269.15
54.14	35	283.48
56.66	36	296.67
59.60	37	312.09
61.19	38	320.37
58.42	39	305.87
54.05	40	283.02
46.54	41	243.70
49.46	42	258.98
51.09	43	267.52
52.13	44	272.95
54.16	45	283.61
54.59	46	285.85
52.48	47	274.79
48.91	48	256.12

Table 5.12. Room and LED luminaire information to compare different uniformity formulas for recommended conditions.

LAMP	**F_{total}**	**Luminaire #**	**# of Lum**
	3700lm	1	40
DIMENSIONS	**Height**	**Width**	**Length**
	2.9 m	3.32 m	5.33m
SURFACES	**r_{wall}**	**r_{ceil}**	**r_{floor}**
	0.6	0.7	0.2
r_{avg}	0.54		
E_{ref}	50.34 lux		

Table 5.13. Results of LED luminaires on selected office, based on maximizing uniformity formula and surface reflectance values for recommended conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	1
Luminaire 2	15
Luminaire 3	33
$E_{avg;Hor}$	**484.25 lux**
Uniformity	**0.71**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.56
E_{wall2}/E_{work}	0.76
E_{wall3}/E_{work}	0.75
E_{wall4}/E_{work}	0.67
LUMINANCE	
$L_{wall1;avg}$	52.26 cd/m^2
$L_{wall2;avg}$	70.69 cd/m^2
$L_{wall3;avg}$	69.34 cd/m^2
$L_{wall4;avg}$	62.86 cd/m^2

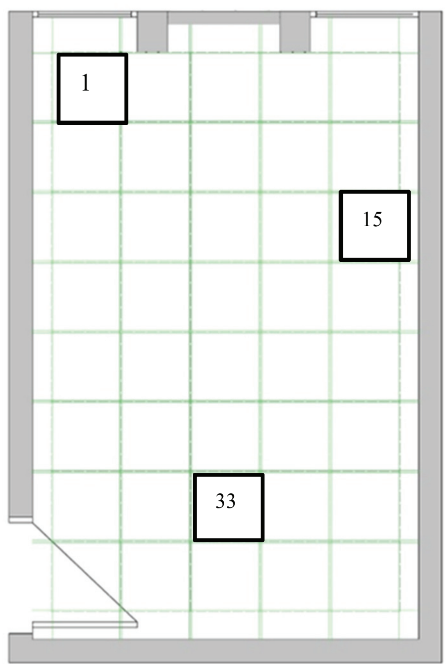


Table 5.14. Luminance and illuminance values on walls results (LED luminaires on selected office) based on maximizing uniformity formula for recommended conditions.

luminance	wall1	illuminance
38.31	1	200.60
45.88	2	240.21
53.17	3	278.41
46.14	4	241.57
38.71	5	202.68
43.20	6	226.17
55.19	7	288.99
66.61	8	348.78
55.44	9	290.31
43.67	10	228.63
48.13	11	252.00
61.48	12	321.88
69.56	13	364.20
61.87	14	323.93
48.79	15	255.49
50.16	16	262.66
58.89	17	308.37
63.00	18	329.89
59.31	19	310.55
50.78	20	265.87
48.80	21	255.50
54.73	22	286.55
56.37	23	295.14
55.08	24	288.39
49.52	25	259.29
47.01	26	246.16
49.65	27	259.97
50.08	28	262.20
50.30	29	263.38
48.08	30	251.73

luminance	wall2	illuminance
38.16	1	199.81
40.93	2	214.31
43.27	3	226.58
52.08	4	272.70
101.88	5	533.43
277.21	6	1451.48
100.61	7	526.79
48.88	8	255.96
43.17	9	226.03
47.94	10	251.02
50.94	11	266.70
64.57	12	338.06
122.48	13	641.32
172.98	14	905.74
120.46	15	630.70
59.83	16	313.29
48.13	17	252.02
53.16	18	278.36
57.76	19	302.40
72.36	20	378.88
98.50	21	515.74
94.33	22	493.90
96.20	23	503.69
66.30	24	347.13
50.92	25	266.61
56.28	26	294.69
62.61	27	327.85
71.08	28	372.18
75.82	29	397.00
65.54	30	343.18
72.91	31	381.77
63.60	32	332.99
50.65	33	265.20
56.15	34	294.01
60.74	35	318.05
66.06	36	345.87
62.54	37	327.46
54.54	38	285.60
59.40	39	311.03
58.85	40	308.13
49.44	41	258.89
53.87	42	282.08
57.85	43	302.88
60.34	44	315.95
55.26	45	289.32
49.69	46	260.18
52.30	47	273.86
54.50	48	285.36

luminance	wall3	illuminance
187.71	1	982.85
87.06	2	455.85
49.35	3	258.42
42.00	4	219.91
39.60	5	207.34
157.24	6	823.30
107.98	7	565.40
60.77	8	318.21
49.37	9	258.50
45.81	10	239.84
97.25	11	509.21
93.49	12	489.53
68.81	13	360.29
55.06	14	288.30
50.91	15	266.54
66.89	16	350.23
74.44	17	389.76
68.10	18	356.55
60.38	19	316.14
54.56	20	285.68
53.93	21	282.37
61.62	22	322.65
64.23	23	336.31
59.09	24	309.39
54.63	25	286.05
47.84	26	250.52
53.82	27	281.81
58.34	28	305.46
56.65	29	296.63
53.13	30	278.19

luminance	wall4	illuminance
37.47	1	196.18
39.30	2	205.76
38.92	3	203.79
38.13	4	199.67
39.83	5	208.55
49.90	6	261.30
100.61	7	526.79
276.19	8	1446.14
42.16	9	220.77
45.37	10	237.56
44.60	11	233.51
43.93	12	230.04
46.57	13	243.85
61.54	14	322.23
120.46	15	630.70
171.28	16	896.80
46.67	17	244.39
50.05	18	262.07
49.94	19	261.46
48.10	20	251.84
51.44	21	269.36
68.51	22	358.73
96.20	23	503.69
92.11	24	482.30
49.40	25	258.65
52.19	26	273.28
53.03	27	277.64
52.24	28	273.54
55.50	29	290.58
66.03	30	345.75
72.91	31	381.77
63.11	32	330.42
48.48	33	253.83
51.73	34	270.88
53.08	35	277.95
54.25	36	284.08
56.88	37	297.82
62.02	38	324.72
59.40	39	311.03
51.38	40	269.00
47.32	41	247.76
49.98	42	261.71
52.08	43	272.68
54.41	44	284.88
56.22	45	294.36
58.09	46	304.13
52.30	47	273.86
46.10	48	241.40

According to results of minimizing uniformity formula; MRD, three luminaires positioned on 9, 21, 39 points as seen on Table 5.15. Average illuminance on working plane is 499.25 lux and uniformity is 0.12. By reason of luminaire located on 21 and 39, there are some results higher than estimated on wall 1 and 4. These calculation points are also located very close to luminaires like fluorescent results (Table 5.16).

Belove results indicate that average illuminance and luminance on walls are satisfying. There are some higher values but they are located above eye level and closer to luminaire location. It may not be uncomfortable for users. Comparing two different uniformity formula is difficult because their illuminance results are close to each other and each formula provides different locations. However, minimizing MRD formula may be a better solution than maximizing uniformity formula (E_{min}/E_{avg}) for the reason that of higher illuminance values on walls of MRD are fewe

Table 5.15. Results of LED luminaires on selected office, based on minimizing uniformity formula and surface reflectance values for recommended conditions.

NUMBER OF LUMINAIRE	**3**
Luminaire 1	9
Luminaire 2	21
Luminaire 3	39
$E_{avg;Hor}$	**499.25 lux**
Uniformity	**0.12**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.76
E_{wall2}/E_{work}	0.61
E_{wall3}/E_{work}	0.54
E_{wall4}/E_{work}	0.73
LUMINANCE	
$L_{wall1;avg}$	73.06 cd/m^2
$L_{wall2;avg}$	58.88 cd/m^2
$L_{wall3;avg}$	52.22 cd/m^2
$L_{wall4;avg}$	69.72 cd/m^2

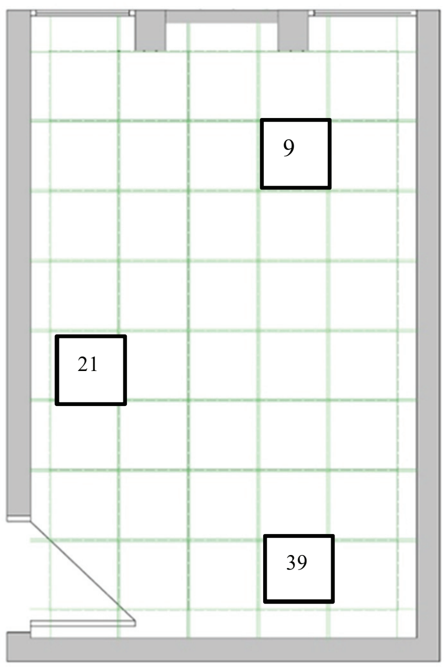


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Table 5.16. Luminance and illuminance values on walls results (LED luminaires on selected office) based on minimizing uniformity formula for recommended conditions.

luminance	wall1	illuminance
38.58	1	202.01
47.92	2	250.90
86.52	3	453.00
187.87	4	983.70
85.39	5	447.12
44.48	6	232.92
58.75	7	307.61
107.45	8	562.60
157.33	9	823.78
105.67	10	553.31
48.78	11	255.43
66.13	12	346.27
92.88	13	486.31
97.37	14	509.80
90.56	15	474.19
53.01	16	277.54
64.91	17	339.85
73.25	18	383.54
67.32	19	352.48
70.63	20	369.80
53.68	21	281.05
61.70	22	323.07
60.38	23	316.17
54.14	24	283.48
57.12	25	299.06
52.74	26	276.16
56.33	27	294.93
52.91	28	277.02
48.12	29	251.94
49.86	30	261.07

luminance	wall2	illuminance
60.59	1	317.25
52.21	2	273.36
42.13	3	220.60
39.98	4	209.32
42.13	5	220.60
52.21	6	273.36
60.59	7	317.25
50.48	8	264.31
76.52	9	400.65
63.56	10	332.81
49.80	11	260.73
46.90	12	245.54
49.80	13	260.73
63.56	14	332.81
76.52	15	400.65
61.28	16	320.87
75.67	17	396.21
69.17	18	362.15
56.60	19	296.33
50.91	20	266.57
56.60	21	296.33
69.17	22	362.15
75.67	23	396.21
66.20	24	346.64
68.50	25	358.67
65.84	26	344.73
59.10	27	309.47
56.61	28	296.44
59.10	29	309.47
65.84	30	344.73
68.50	31	358.67
62.25	32	325.92
58.96	33	308.69
60.73	34	317.97
59.97	35	313.99
58.13	36	304.36
59.97	37	313.99
60.73	38	317.97
58.96	39	308.69
56.54	40	296.07
52.24	41	273.50
55.61	42	291.17
57.37	43	300.40
57.07	44	298.80
57.37	45	300.40
55.61	46	291.17
52.24	47	273.50
50.74	48	265.66

luminance	wall3	illuminance
34.98	1	183.16
39.41	2	206.34
46.63	3	244.17
53.49	4	280.08
45.94	5	240.53
38.95	6	203.96
44.64	7	233.73
56.15	8	294.01
67.13	9	351.50
55.31	10	289.59
42.06	11	220.25
50.22	12	262.95
62.85	13	329.08
70.05	14	366.76
61.70	15	323.05
44.91	16	235.16
52.39	17	274.30
60.45	18	316.53
63.70	19	333.55
59.16	20	309.74
46.29	21	242.36
51.77	22	271.06
56.54	23	296.04
57.17	24	299.32
55.01	25	288.02
46.46	26	243.25
50.49	27	264.38
51.88	28	271.62
50.96	29	266.81
49.96	30	261.61

luminance	wall4	illuminance
39.60	1	207.34
50.39	2	263.85
101.39	3	530.86
277.47	4	1452.81
101.39	5	530.86
50.39	6	263.85
39.60	7	207.34
35.32	8	184.96
45.67	9	239.12
62.11	10	325.20
121.95	11	638.54
173.60	12	908.96
121.95	13	638.54
62.11	14	325.20
45.67	15	239.12
39.76	16	208.19
50.01	17	261.83
69.41	18	363.42
97.93	19	512.75
95.16	20	498.24
97.93	21	512.75
69.41	22	363.42
50.01	23	261.83
42.95	24	224.90
55.04	25	288.20
67.82	26	355.08
75.15	27	393.47
66.20	28	346.63
75.15	29	393.47
67.82	30	355.08
55.04	31	288.20
46.34	32	242.64
55.30	33	289.57
63.16	34	330.71
61.90	35	324.10
55.59	36	291.08
61.90	37	324.10
63.16	38	330.71
55.30	39	289.57
48.29	40	252.83
53.59	41	280.60
58.12	42	304.33
54.72	43	286.51
50.72	44	265.56
54.72	45	286.51
58.12	46	304.33
53.59	47	280.60
48.58	48	254.34

The above results motivate to run OptimLUM for different dimensions. Same fluorescent luminaires and same reflectance values for surfaces were applied to model. The length of the office is 4.5 m in the Y-direction, its width is 4.5 m in the X-direction and ceiling height is 2.9 m.

Table 5.17. Room dimension, surfaces and fluorescent luminaire information for recommended conditions with different room sizes.

LAMP	**F_{total}**	**Luminaire #**	**# of Lum**
	3780lm	2	40
DIMENSIONS	**Height**	**Width**	**Length**
	2.9 m	4.5 m	4.5 m
SURFACES	**r_{wall}**	**r_{ceil}**	**r_{floor}**
	0.6	0.7	0.2
r_{avg}	0.53		
E_{ref}	46.81 lux		

Table 5.18. Results of fluorescent luminaires on selected office, based on maximizing uniformity formula and different dimensions.

NUMBER OF LUMINAIRE	**4**
Luminaire 1	40
Luminaire 2	2
Luminaire 3	36
Luminaire 4	21
$E_{avg;Hor}$	**484.52 lux**
Uniformity	0.75
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.66
E_{wall2}/E_{work}	0.76
E_{wall3}/E_{work}	0.73
E_{wall4}/E_{work}	0.79
LUMINANCE	
$L_{wall1;avg}$	60.91 cd/m^2
$L_{wall2;avg}$	70.86 cd/m^2
$L_{wall3;avg}$	67.84 cd/m^2
$L_{wall4;avg}$	72.83 cd/m^2

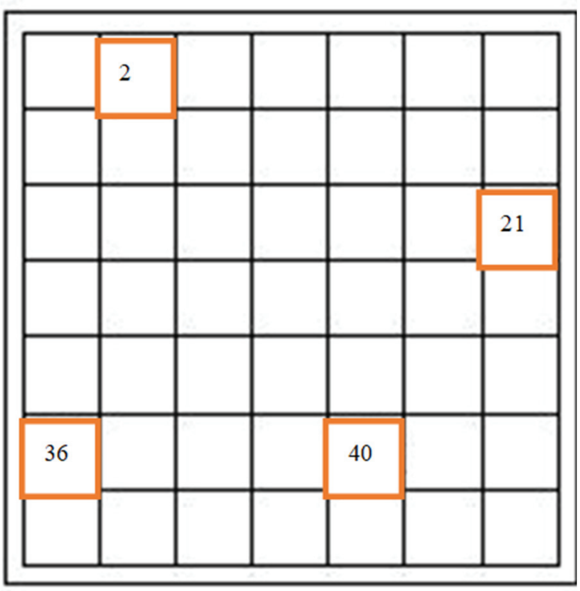


Table 5.19. Luminance and illuminance values on walls results (fluorescent luminaires on selected office) based on maximizing uniformity formula and different dimensions.

luminance	wall1	illuminance	luminance	wall2	illuminance	luminance	wall3	illuminance	luminance	wall4	illuminance
40.87	1	213.97	35.83	1	187.59	84.33	1	441.56	84.33	1	441.57
37.00	2	193.75	35.87	2	187.83	270.22	2	1414.88	270.23	2	1414.90
35.91	3	188.05	36.04	3	188.68	84.34	3	441.58	84.34	3	441.60
37.01	4	193.76	84.35	4	441.66	36.01	4	188.54	36.02	4	188.61
40.87	5	213.99	270.23	5	1414.91	35.83	5	187.63	35.88	5	187.87
36.99	6	193.67	84.33	6	441.57	35.83	6	187.60	36.99	6	193.70
35.85	7	187.72	36.00	7	188.50	35.85	7	187.69	40.86	7	213.96
77.94	8	408.07	39.25	8	205.51	114.22	8	598.03	114.23	8	598.12
65.98	9	345.50	44.18	9	231.35	138.04	9	722.76	138.06	9	722.86
52.56	10	275.19	61.83	10	323.75	114.24	10	598.15	114.27	10	598.30
65.99	11	345.52	115.26	11	603.48	58.48	11	306.21	59.45	11	311.25
77.95	12	408.14	138.09	12	723.01	38.72	12	202.74	46.06	12	241.18
65.00	13	340.34	114.23	13	598.13	39.25	13	205.53	65.03	13	340.51
44.19	14	231.39	58.43	14	305.92	42.32	14	221.56	77.92	14	407.97
75.32	15	394.35	52.45	15	274.60	82.84	15	433.76	83.47	15	437.05
73.94	16	387.18	63.49	16	332.44	78.08	16	408.83	78.88	16	413.01
73.72	17	386.02	79.46	17	416.03	83.49	17	437.15	85.00	17	445.07
74.08	18	387.90	90.23	18	472.45	68.79	18	360.20	72.52	18	379.73
75.77	19	396.71	80.90	19	423.61	53.87	19	282.08	65.54	19	343.19
68.60	20	359.18	83.48	20	437.09	52.46	20	274.70	70.65	20	369.92
55.44	21	290.26	65.94	21	345.28	53.33	21	279.21	74.25	21	388.78
67.34	22	352.61	58.84	22	308.09	63.48	22	332.39	65.35	22	342.17
71.76	23	375.76	67.66	23	354.29	58.47	23	306.17	61.71	23	323.11
72.93	24	381.88	76.10	24	398.43	65.92	24	345.17	70.15	24	367.29
72.78	25	381.07	73.77	25	386.24	67.51	25	353.50	72.99	25	382.19
69.46	26	363.71	63.75	26	333.77	62.18	26	325.55	69.79	26	365.43
64.91	27	339.86	65.83	27	344.67	59.53	27	311.71	67.67	27	354.32
57.92	28	303.28	61.41	28	321.54	55.99	28	293.18	64.75	28	339.03
61.35	29	321.22	59.23	29	310.14	55.70	29	291.66	58.20	29	304.74
66.11	30	346.14	64.91	30	339.88	52.98	30	277.39	56.03	30	293.40
69.01	31	361.36	68.53	31	358.84	60.05	31	314.40	64.09	31	335.56
67.71	32	354.52	64.87	32	339.64	64.59	32	338.19	68.74	32	359.93
64.39	33	337.16	57.72	33	302.22	63.59	33	332.93	67.81	33	355.03
61.81	34	323.63	58.98	34	308.82	60.78	34	318.23	63.92	34	334.71
58.01	35	303.72	57.61	35	301.63	57.08	35	298.85	58.95	35	308.64
57.39	36	300.49	57.59	36	301.57	52.86	36	276.77	55.12	36	288.63
61.25	37	320.69	61.31	37	321.04	51.78	37	271.09	54.28	37	284.20
63.60	38	333.01	62.67	38	328.12	57.16	38	299.31	60.51	38	316.85
63.27	39	331.30	59.76	39	312.92	61.65	39	322.82	64.49	39	337.66
60.79	40	318.28	54.74	40	286.60	61.87	40	323.97	64.23	40	336.31
59.06	41	309.22	55.62	41	291.21	59.57	41	311.88	60.39	41	316.19
56.58	42	296.24	55.56	42	290.91	55.96	42	292.99	55.69	42	291.62

According to E_{min}/E_{avg} uniformity formula, four luminaires positioned on 2, 21, 36, 40 points as seen on Table 5.18. Average illuminance on working plane is 484.52 lux and uniformity is 0.75. Uniformity value is between recommended range (>0.7). Only three values that are higher than expected are located very close to luminaires. Due to luminaire located on 2, 21, 36 these higher values can be observed on wall 2, 3 and 4 (Table 5.19).

According to results of MRD uniformity formula, four luminaires positioned on 2, 13, 36, 40 points as seen on Table 5.20. Average illuminance on working plane is 492.12 lux and uniformity is 0.07. Illuminance result is satisfying and uniformity value is very close to zero as recommended value. Due to luminaire located on 2 and 36, higher luminance values can be observed on wall 3 and 4. These calculation points are also located very close to luminaires like other results. As mentioned before, higher illuminance and luminance values on walls of MRD are fewer (Table 5.21).

Table 5.20. Results of fluorescent luminaires on selected office, based on minimizing uniformity formula and different dimensions.

NUMBER OF LUMINAIRE	**4**
Luminaire 1	40
Luminaire 2	2
Luminaire 3	36
Luminaire 4	13
$E_{avg;Hor}$	**492.12 lux**
Uniformity	**0.07**
ILLUMINANCE RATIO	
E_{wall1}/E_{work}	0.64
E_{wall2}/E_{work}	0.59
E_{wall3}/E_{work}	0.80
E_{wall4}/E_{work}	0.78
LUMINANCE	
$L_{wall1;avg}$	60.30 cd/m^2
$L_{wall2;avg}$	55.57 cd/m^2
$L_{wall3;avg}$	74.92 cd/m^2
$L_{wall4;avg}$	73.22 cd/m^2

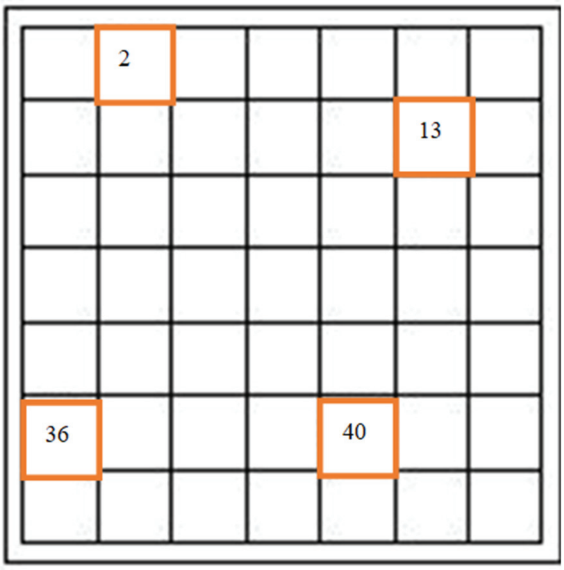


Table 5.21. Luminance and illuminance values on walls results (fluorescent luminaires on selected office) based on minimizing uniformity formula and different dimensions.

luminance	wall1	illuminance
40.87	1	213.97
37.00	2	193.75
35.91	3	188.05
37.00	4	193.76
40.87	5	213.98
36.99	6	193.66
35.85	7	187.70
77.94	8	408.07
65.98	9	345.49
52.56	10	275.19
65.99	11	345.51
77.94	12	408.09
64.98	13	340.25
44.17	14	231.29
75.32	15	394.35
73.94	16	387.17
73.72	17	385.99
73.95	18	387.21
75.33	19	394.44
67.97	20	355.88
54.78	21	286.84
67.34	22	352.61
71.76	23	375.73
72.82	24	381.30
71.98	25	376.89
68.11	26	356.60
63.00	27	329.84
55.34	28	289.74
61.35	29	321.23
66.09	30	346.05
68.67	31	359.54
66.77	32	349.59
62.77	33	328.68
59.10	34	309.42
55.14	35	288.72
57.40	36	300.53
61.22	37	320.53
63.18	38	330.82
62.06	39	324.97
58.98	40	308.82
56.73	41	297.05
53.78	42	281.61

luminance	wall2	illuminance
35.82	1	187.55
35.85	2	187.70
35.84	3	187.65
35.87	4	187.81
36.99	5	193.70
40.87	6	213.97
36.99	7	193.65
39.20	8	205.25
42.33	9	221.66
40.21	10	210.52
45.22	11	236.75
65.03	12	340.50
77.93	13	408.02
64.98	14	340.24
49.76	15	260.56
54.39	16	284.79
55.75	17	291.93
62.18	18	325.55
70.65	19	369.90
74.44	20	389.78
67.81	21	355.06
53.84	22	281.90
58.52	23	306.42
63.23	24	331.07
65.69	25	343.95
67.67	26	354.32
65.80	27	344.53
62.14	28	325.38
54.21	29	283.82
58.96	30	308.72
62.71	31	328.36
64.64	32	338.45
63.68	33	333.44
60.68	34	317.73
58.00	35	303.69
53.93	36	282.36
57.76	37	302.45
60.27	38	315.56
61.50	39	322.03
59.87	40	313.50
57.29	41	299.99
55.42	42	290.17

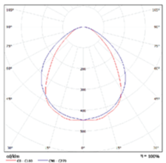
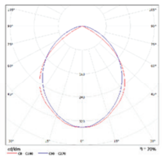
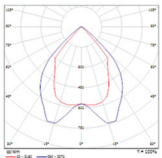
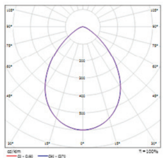
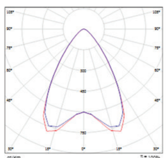
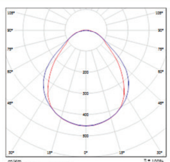
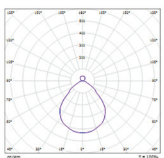
luminance	wall3	illuminance
84.33	1	441.57
270.23	2	1414.90
84.35	3	441.67
36.07	4	188.84
37.02	5	193.81
40.87	6	214.00
36.99	7	193.66
114.22	8	598.06
138.07	9	722.92
115.23	10	603.33
66.81	11	349.82
66.86	12	350.10
77.96	13	408.20
64.99	14	340.28
83.13	15	435.28
79.48	16	416.13
89.12	17	466.63
84.77	18	443.83
78.31	19	410.05
76.77	20	401.99
68.13	21	356.73
64.95	22	340.08
62.61	23	327.81
74.09	24	387.96
79.06	25	413.95
75.58	26	395.75
69.75	27	365.20
63.13	28	330.55
57.93	29	303.30
57.68	30	302.03
66.22	31	346.74
71.66	32	375.19
69.31	33	362.93
64.10	34	335.61
59.53	35	311.67
55.41	36	290.15
55.49	37	290.56
61.15	38	320.17
65.23	39	341.53
63.85	40	334.34
59.82	41	313.22
56.28	42	294.70

luminance	wall4	illuminance
84.33	1	441.57
270.23	2	1414.90
84.34	3	441.60
36.02	4	188.61
35.88	5	187.87
37.00	6	193.71
40.87	7	213.97
114.23	8	598.12
138.06	9	722.87
114.27	10	598.30
59.45	11	311.27
46.07	12	241.20
65.04	13	340.53
77.92	14	407.99
83.47	15	437.07
78.88	16	413.03
85.01	17	445.10
72.53	18	379.79
65.56	19	343.26
70.67	20	370.01
74.27	21	388.86
65.35	22	342.17
61.80	23	323.56
70.26	24	367.88
73.30	25	383.81
70.39	26	368.59
68.38	27	358.02
65.45	28	342.68
58.26	29	305.07
56.54	30	296.02
64.65	31	338.52
69.67	32	364.81
69.20	33	362.34
65.37	34	342.30
60.63	35	317.44
55.35	36	289.79
54.80	37	286.93
61.23	38	320.58
65.61	39	343.56
65.50	40	342.96
62.31	41	326.23
57.30	42	300.01

5.1.2. Selection of Luminaire Types and Room Dimensions

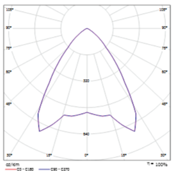
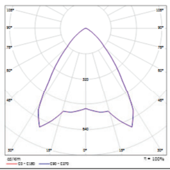
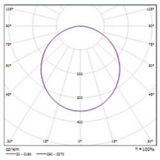
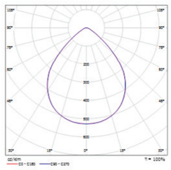
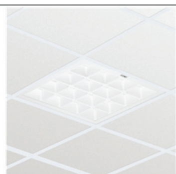
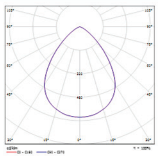
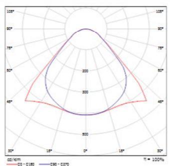
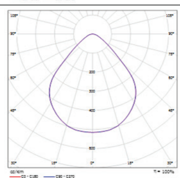
A luminaire database for offices was generated for OptimLUM users to select luminaire type effortlessly. This database includes luminous flux and photometric data of luminaires from various manufacturers. Photometric data not only provides luminous intensity of luminaires that varies according to vertical (Gamma) and horizontal (C) angles but also makes it possible to calculate illuminance (Table 5.22).

Table 5.22. Database for OptimLUM users.

	NAME	DISTRIBUTION CURVE	PICTURE	SYSTEM FLUX	EFFICACY	LUMINAIRE POWER
1	PHILIPS CoreLine Surface-mounted (SM120V LED37S/840 PSU W60L60)			3700 lumen	93 lm/W	42 W
2	PHILIPS Centura 2 (TCS160 4xTL-D18W HF C3)			3780 lumen	209 lm/W	69.5 W
3	OSRAM SITECO 51MT1LV0JHGEB B02 Taris®2			3930 lumen	131 lm/W	30 W
4	OSRAM SITECO 0DX11A7833S LEDVALUX® XL (Lunis)			1970 lumen	104 lm/W	19 W
5	OSRAM SITECO 5MZ212D03WA Scriptus®			2195 lumen	127 lm/W	17.3 W
6	Zumtobel 42185186 MLevo AA LED3600-840 Q LDO SR			3450 lumen	115 lm/W	30.4 W
7	Zumtobel 42184475 LFE DI LED4600-840 Q LDO ASH1 SRE (Light Fields)			4530 lumen	121 lm/W	37.5 W

(cont. on next page)

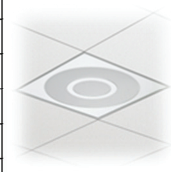
Table 5.22. (cont.)

	NAME	DISTRIBUTION CURVE	PICTURE	SYSTEM FLUX	EFFICACY	LUMINAIRE POWER
8	Zumtobel 42182361 MIREL-L LAY LED3800-840 M600Q EVG KA			3740 lumen	134 lm/W	28 W
9	Zumtobel 42925916 MIREL-L LAY LED2800-830 M600Q LDO KA			2600 lumen	130 lm/W	20 W
10	Zumtobel 42182369 MIREL-O NIV LED3800-840 M600Q EVG KA			3710 lumen	139 lm/W	26.7 W
11	PHILIPS RC461B G2 PSD W60L60 1xLED34S/840 (smartbalance)			3400 lumen	142 lm/W	25 W
12	PHILIPS DN570B PSED-E 1xLED20S/830 C PG (LuxSpace)			2100 lumen	111 lm/W	19 W
13	PHILIPS SP480P W24L134 1xLED35S/830 ACC-MLO (smartbalance)			3500 lumen	119 lm/W	37 W
14	PHILIPS BBS560 1xLED35S/840 AC-MLO-C (dayzone)			3500 lumen	103 lm/W	34 W

This database includes different type of luminaires like downlight, mounted and suspended. Besides variances of installation types, their system fluxes differentiate between 1970 lumen and 4530 lumen. They are divided into three groups; low, medium and high. Luminous efficacy is an important metric that improve lighting quality. Luminous efficacy of luminaires in database is also divided into three groups to evaluate their results. Table 5.23.

Table 5.23. Grouping of luminaires according to their system flux, luminaire type and luminous efficacy.

	#	SYSTEM FLUX
LOW	4	1970 lumen
	12	2100 lumen
	5	2195 lumen
	9	2600 lumen
MIDDLE	11	3400 lumen
	6	3450 lumen
	13	3500 lumen
	14	3500 lumen
	1	3700 lumen
	10	3710 lumen
HIGH	8	3740 lumen
	2	3780 lumen
	3	3930 lumen
	7	4530 lumen

LUMINAIRE TYPE	#	
DOWNLIGHT	4	
	12	
MOUNTED	1	
	2	
	3	
	6	
	8	
	9	
	10	
	13	
	14	
SUSPENDED	5	
	7	
	13	

	#	LUMINOUS EFFICACY
LOW	1	93 lm/W
	14	103 lm/W
	4	104 lm/W
	12	111 lm/W
MIDDLE	6	115 lm/W
	13	119 lm/W
	7	121 lm/W
	5	127 lm/W
	9	130 lm/W
	3	131 lm/W
HIGH	8	134 lm/W
	10	139 lm/W
	11	142 lm/W
	2	209 lm/W

The objective of the OptimLUM is to achieve energy efficient luminaire layouts for different volumes. Besides a luminaire database, three different room types are identified to evaluate OptimLUM layouts. Small, medium and large space are well-defined with different room indices. Room index K is a function of the room dimensions and is calculated using the range of horizontal surfaces to vertical surfaces. By keeping height as constant, room index increases while length and width are getting higher.

$$K = \frac{L*W}{H_m(L+W)} \quad (5.13)$$

L: Room length.

W: Room width.

H_m: Mounting height of fitting (from working plane).

Different room indices and volume dimensions can provide these values for the purpose of representing small, medium and large volumes are determined with a similar approach to (Stockmar 2002) and (Ceelen 2002)'s comparative approach to armatures. In this context, the ceiling height is kept constant at 3 meters. Small, medium and large volumes are defined as multiples of the smallest volume dimensions. Emre (2012) used also same room indices to evaluate lighting requirements for different types of buildings. These three determined room dimensions are presented in Figure 5.2.

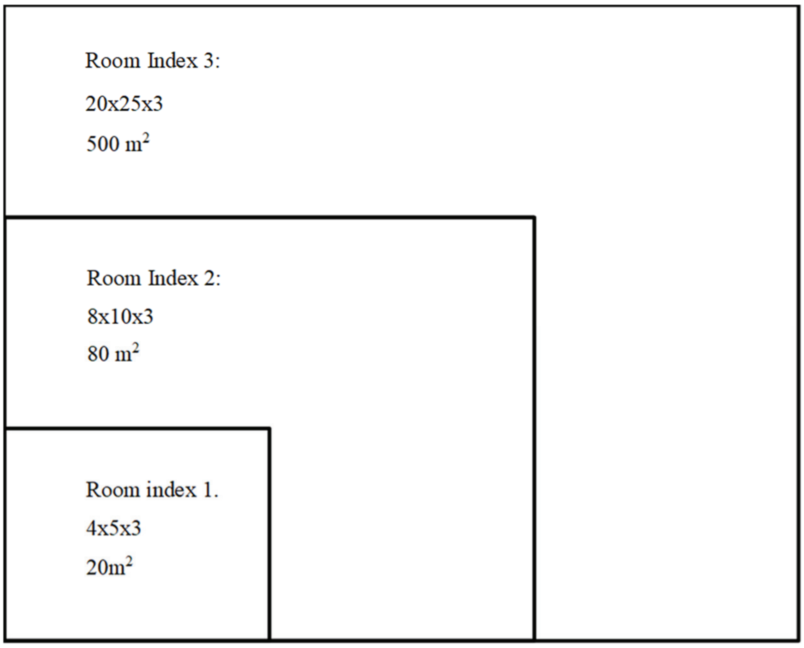


Figure 5.2. Room indices and dimensions for small, medium and large spaces.

5.2. Energy Efficient Luminaire Layout Solutions

Considering the progress steps of OptimLUM, the model has reached its final use. Uniformity formula is defined. The model works in 3D by calculating and adding constraints about luminance on walls, illuminance of vertical and horizontal surfaces. Figure 5.3 shows the flow chart of the final phase of OptimLUM.

In this phase, model runs for different volumes with different luminaires to guide users to effectively evaluate estimations of the OptimLUM about the accurate location, number and type of light sources in an office in the early design phase. According to luminaire type and room size, obtained results about E_{avg} on work plane, ratio of illuminance on wall to work plane (E_{wall}/E_{work}), luminance values on walls, valid trials, total trials and total optimization time can be read in the Appendix B by tables.

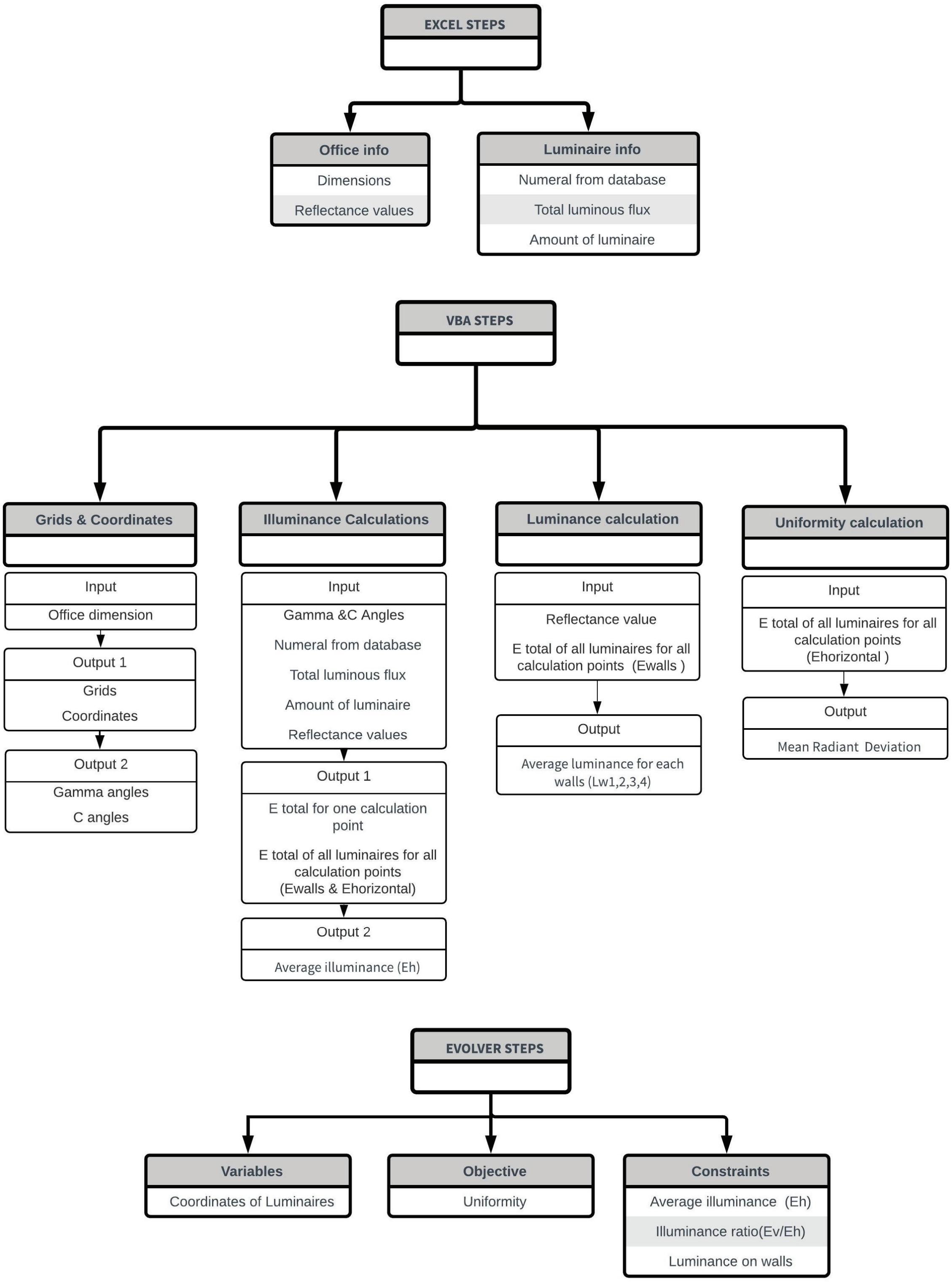


Figure 5.3. Flow chart of OptimLUM.

Table 5.24. General information about luminaires and their results based on OptimLUM estimation for small room.

SMALL ROOM							
Luminaire	**LF**	**LP**	**LE**	**#**	**E_{avg}**	**U**	**LPD**
1	3700 lumen	42 W	93 lm/W	3	446.69 lux	0.11	6.5 W/m^2
2	3780 lumen	69.5 W	209 lm/W	4	476.82 lux	0.05	13.5 W/m^2
3	3930 lumen	30 W	131 lm/W	3	476.90 lux	0.21	4.5 W/m^2
4	1970 lumen	19 W	104 lm/W	5	409.63 lux	0.05	4.75 W/m^2
5	2195 lumen	17.3 W	127 lm/W	5	414.43 lux	0.09	4.3 W/m^2
6	3450 lumen	30.4 W	115 lm/W	3	411.97 lux	0.11	4.56 W/m^2
7	4530 lumen	37.5 W	121 lm/W	3	499.57 lux	0.23	5.63 W/m^2
8	3740 lumen	28 W	134 lm/W	3	480.47 lux	0.25	4.2 W/m^2
9	2600 lumen	20 W	130 lm/W	4	442.84 lux	0.06	4 W/m^2
10	3710 lumen	26.7 W	139 lm/W	3	445.39 lux	0.03	4 W/m^2
11	3400 lumen	25W	142 lm/W	3	409.56 lux	0.20	3.75 W/m^2
12	2100 lumen	19W	111 lm/W	5	452.46 lux	0.05	4.75 W/m^2
13	3500 lumen	37 W	119 lm/W	3	440.93 lux	0.11	5.55 W/m^2
14	3500 lumen	34 W	103 lm/W	3	499.59 lux	0.15	5.1 W/m^2

Luminaire 1 is a wide angle LED luminaire with high luminous flux. Luminaire 2 is a luminaire with fluorescent lamp together with narrow angle distribution curve. According to outputs of OptimLUM, for small room, three luminaires numbered 1 have reached optimum results with satisfactory uniformity 0.11. Even though, luminaire with fluorescent lamps has approximate luminous flux to luminaire with LED, 4 luminaires are located in the space because of its narrow distribution. Luminaire 2 (fluorescent) has a better uniformity value; 0.05. However, it can be said that energy efficiency of fluorescent luminaire is very low due to very high luminaire power density which is 13.5 W/m^2.

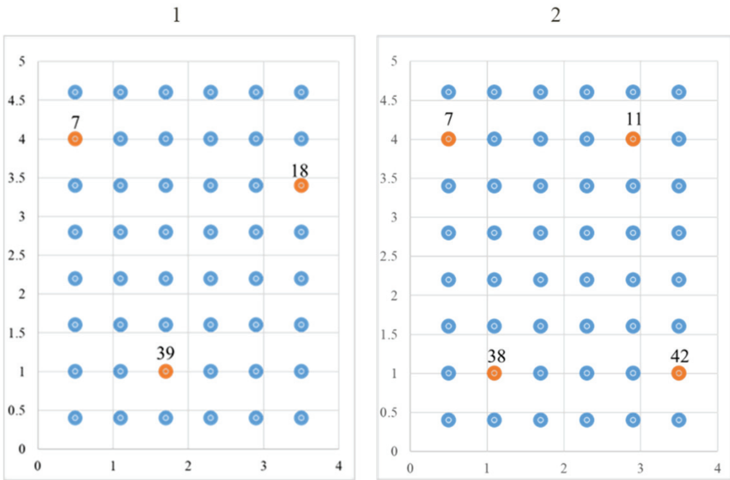


Figure 5.4. OptimLUM layouts for small room with luminaires 1 and 2.

Luminaire 8 and 11 have similar luminous flux with luminaire 1 and 2. Luminaire 8 light output graphs differentiate from other luminaires with its distribution on X and Y direction. Luminaire numbered 3 and 7 have the highest luminous flux which are respectively 3930 and 4530 lumen. Candle power distribution of Luminaire 3 on x-direction is different from y-direction. In small room, with 3 light sources, these luminaire numbered 3, 7, 8 and 11 which have dissimilar, special features give similar, satisfactory results about vertical and horizontal illuminance and also luminance but their uniformity values are above 0.2 which is poor by comparing other luminaires' outputs. Figure 5.5 and Figure 5.6 show their location in the small office. There is no chance to calculate with four luminaires in small room due to over value of E_{avg}.

Figure 5.5. OptimLUM layouts for small room with luminaires 3 and 7.

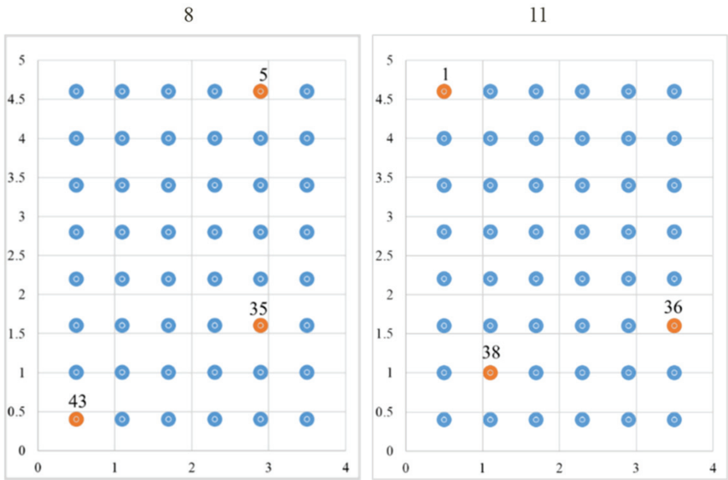


Figure 5.6. OptimLUM layouts for small room with luminaires 8 and 11.

Luminaire 4 and 12 are downlight luminaires with narrow beam angles. Their luminous flux are low and respectively, 1970 and 2100 lumen. Luminaire power values are equal; 19W and accordingly, luminance efficacy of luminaire 4 is higher than 12. With 5 light sources, these two luminaire type provide uniform lighting and the comfort conditions with adequate illuminance and luminance values for small room. The energy consumed per square meter are also equal and 4.75 W/m2. As can be seen in Figure 5.7, luminaires located in the same way at the room.

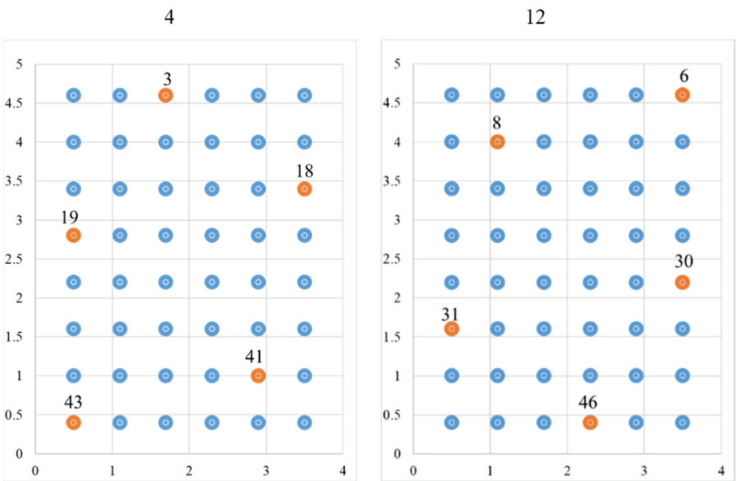


Figure 5.7. OptimLUM layouts for small room with luminaires 4 and 12.

Likewise the Table 5.24, to evaluate results for different types of luminaires, Table 5.25 illustrates the general information about luminous flux, luminaire power, luminous efficacy of each luminaire and their OptimLUM outputs about E_{avg}, uniformity and luminaire power density for medium room.

Table 5.25. General information about luminaires and their results based on OptimLUM estimation for medium room.

MEDIUM ROOM							
Luminaire	**LF**	**LP**	**LE**	**#**	**Eavg**	**U**	**LPD**
1	3700 lumen	42 W	93 lm/W	8	375.62 lux	0.15	4.2 W/m^2
2	3780 lumen	69.5 W	209 lm/W	10	389.05 lux	0.10	8.68 W/m^2
3	3930 lumen	30 W	131 lm/W	8	392.12 lux	0.29	3 W/m^2
				9	471.93 lux	0.19	3.37 W/m^2
4	1970 lumen	19 W	104 lm/W	14	354.30 lux	0.12	3.32 W/m^2
5	2195 lumen	17.3 W	127 lm/W	14	410.27 lux	0.15	3.02 W/m^2
6	3450 lumen	30.4 W	115 lm/W	8	345.06 lux	0.18	3.04 W/m^2
7	4530 lumen	37.5 W	121 lm/W	7	388.18 lux	0.17	3.28 W/m^2
8	3740 lumen	28 W	134 lm/W	8	397.07 lux	0.27	2.8 W/m^2
				9	468.12 lux	0.19	3.15 W/m^2
9	2600 lumen	20 W	130 lm/W	12	417.49 lux	0.12	3 W/m^2
10	3710 lumen	26.7 W	139 lm/W	8	384.31 lux	0.11	2.67 W/m^2
11	3400 lumen	25W	142 lm/W	8	338.93 lux	0.29	2.5 W/m^2
				9	406.27 lux	0.14	2.81 W/m^2
12	2100 lumen	19W	111 lm/W	13	351.27 lux	0.15	3.08 W/m^2
13	3500 lumen	37 W	119 lm/W	8	368.72 lux	0.13	3.7 W/m^2
14	3500 lumen	34 W	103 lm/W	8	362.92 lux	0.16	3.4 W/m^2

Similar results with Luminaire 1 and 2 obtained for small room are attained for medium room. Better uniformity has been provided with Luminaire 2 but the energy used per square meter is more than lighting with luminaire 1. LPD value of outputs with luminaire 1 is 4.2 W/ m^2 when the LPD of Luminaire 2 is 8.68 W/m^2.

For medium room, in trials with a minimum number of artificial light sources; eight luminaires, uniformity values of luminaire 3, 8 and 11 are similarly unsatisfactory like small room. Their locations are shown in Figure 5.8. With nine luminaires, the optimization problem has tried to be solved. According their outputs, not only recommended comfort conditions were obtained but also uniformity value gets lower under 0.2. Uniformity value is decreased from 0.29 to 0.19 for Luminaire 3.

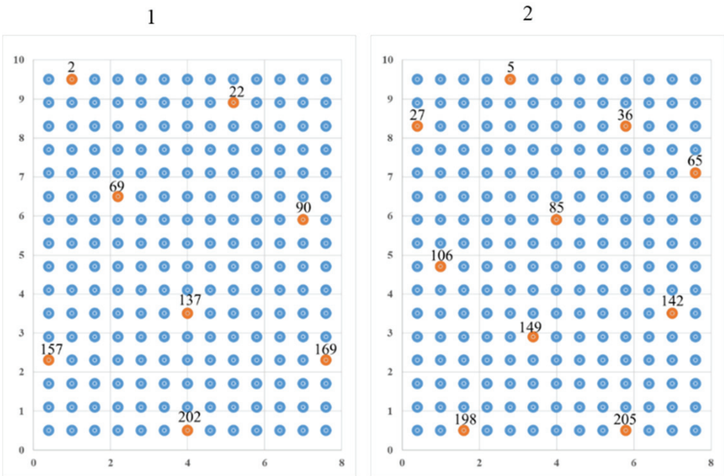


Figure 5.8. OptimLUM layouts for medium room with luminaires 1 and 2.

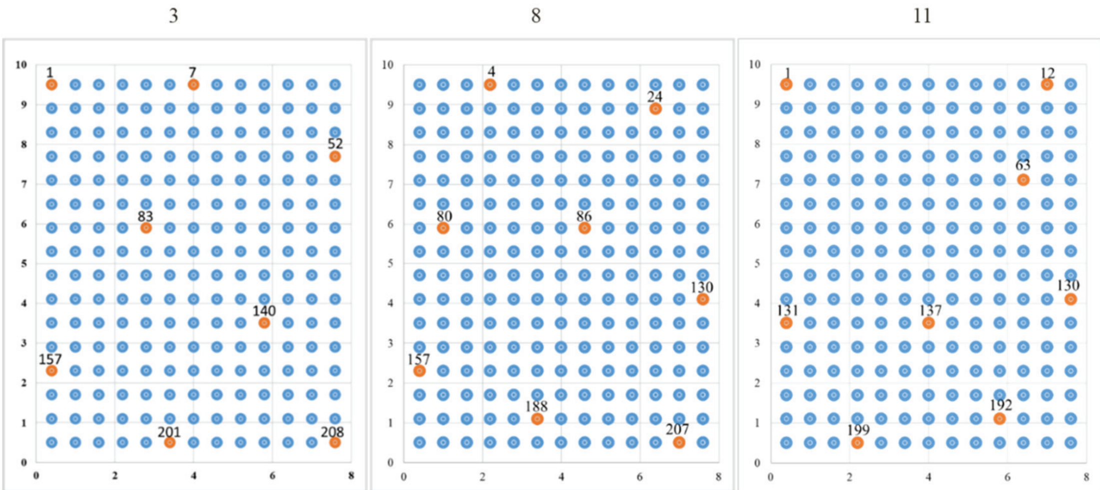


Figure 5.9. OptimLUM layouts for medium room with eight luminaires 3, 8 and 11.

Similarly, for luminaire 8, it drops off from 0.27 to 0.19. For luminaire 11, a high reduction was observed from 0.29 to 0.14. By comparing Figure 5.8 and 5.9, it can be noticed that distributions of luminaires' location are also more uniform in Figure 5.9. Nevertheless, accordingly, their LPD values are increased. On the other hand, different results may be observed when considering daytime using situations. As it will be mentioned in integration with daylight results (subheading 5.3), users could choose between outputs by priority of better uniformity or energy efficiency according to office hours and daylight conditions.

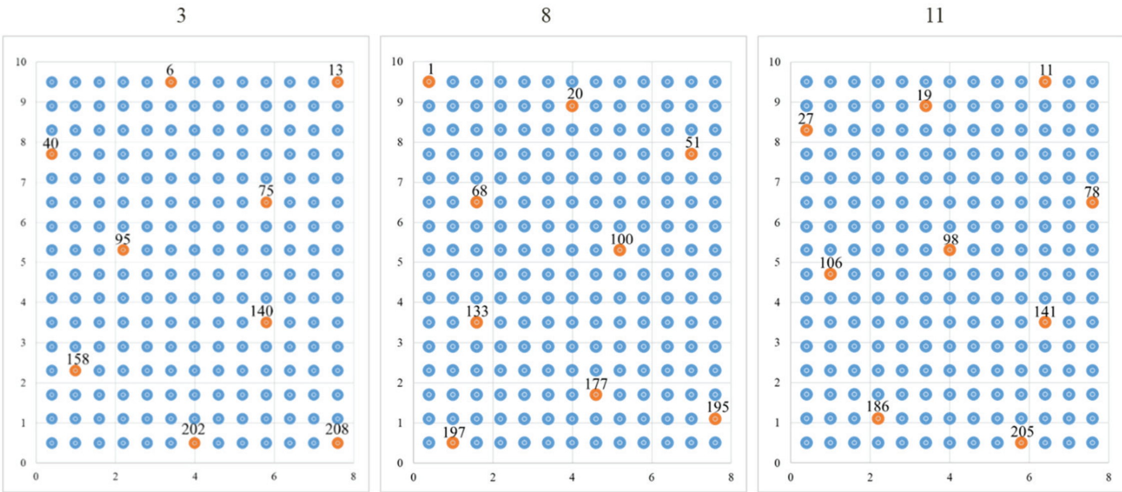


Figure 5.10. OptimLUM layouts for medium room with nine luminaires 3, 8 and 11.

With downlight luminaires 4 and 12 the same results and similar layouts were observed for small room. But their layouts and accordingly their results differentiate from each other for medium room. Fourteen luminaires numbered 4 provide recommended lighting conditions with the U value 0.12 while thirteen luminaires numbered 12 achieve these conditions with the U value 0.15. Luminaire 4 is less energy efficient with high LPD value while it offers better uniformity for medium room. OptimLUM user could select according to his/her priority of better uniformity or energy efficiency by comparing these same type of luminaire.

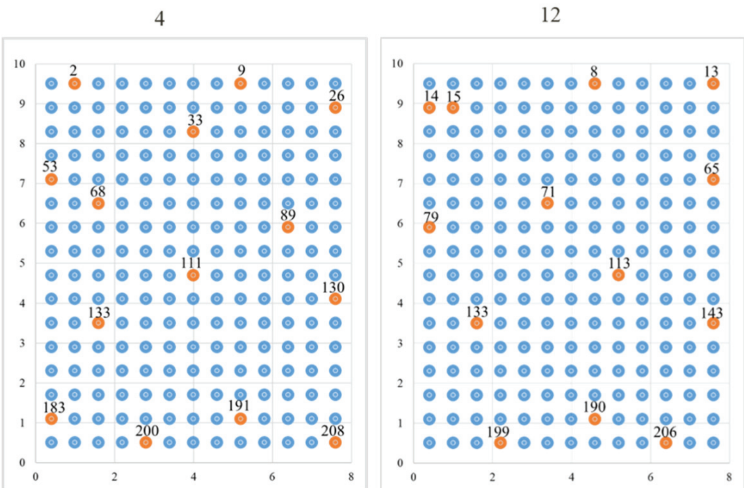
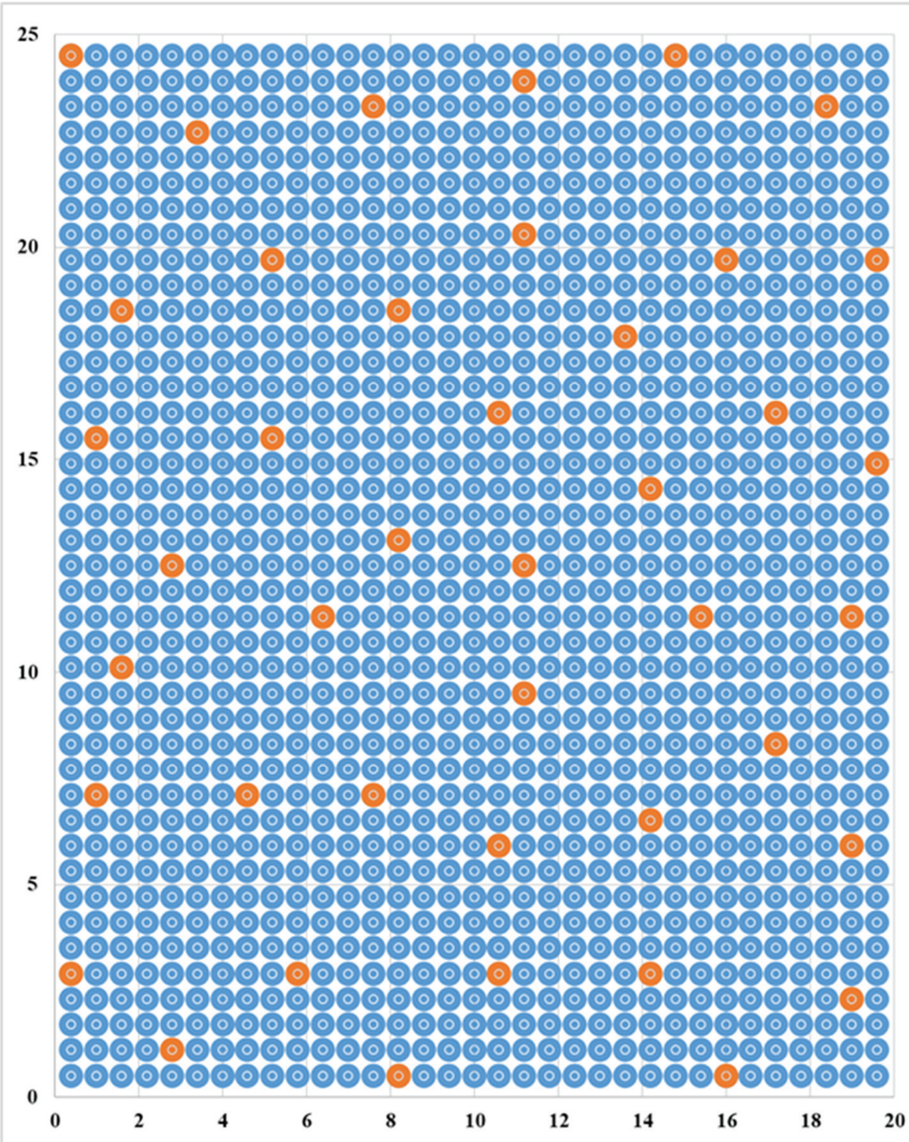


Figure 5.11. OptimLUM layouts for medium room with nine luminaires 4 and 12.

Luminaire 1 and 2 give similar results about LPD and uniformity values for large room. According to these outputs of OptimLUM located forty-two luminaires numbered 1 with the uniformity value 0.16. Luminaire 2 (fluorescent) has a better uniformity value; 0.11. However, like their other performances in small and medium room, better uniformity has been provided with Luminaire 2 but the energy used per square meter is more than lighting with luminaire 1.

Table 5.26. Layout of OptimLUM estimation for large room with forty-two Luminaire 1 and results based on OptimLUM estimation for large room.

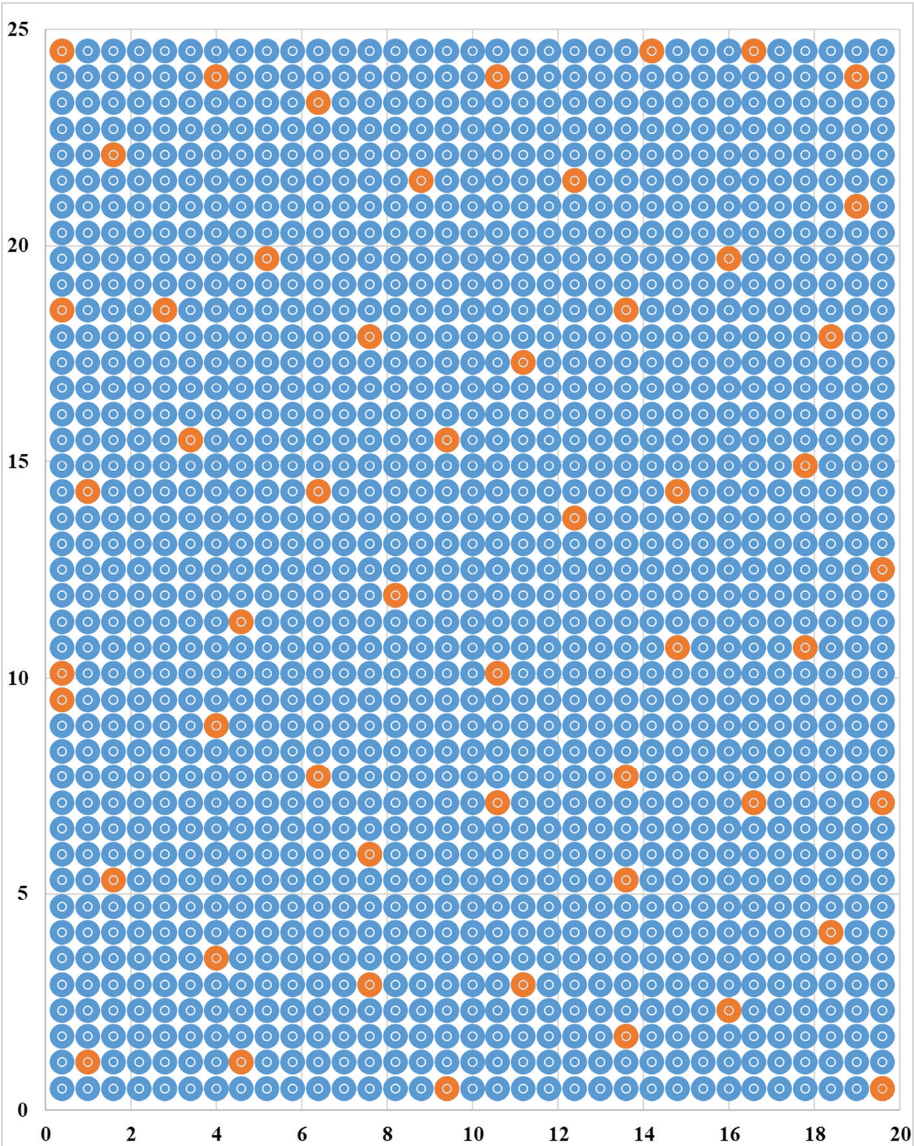
LARGE ROOM



Luminaire	LF	LP	LE	#	Eavg	U	LPD
1	3700 lumen	42 W	93 lm/W	42	385.13lux	0.16	3.53 W/m^2

Table 5.27. Layout of OptimLUM estimation for large room with fifty-five Luminaire 2 and results based on OptimLUM estimation for large room.

LARGE ROOM



Luminaire	LF	LP	LE	#	Eavg	U	LPD
2	3780 lumen	69.5 W	209 lm/W	54	396.07 lux	0.11	7.50 W/m^2

5.3. OptimLUM- Daylight Integration

Offices are places that are used throughout the day. Although all lighting is provided with artificial lighting for the darkest conditions, daylighting of spaces during daytime and the integration of daylight and artificial lighting should be considered for the insufficient daytime lighting conditions. For this reason, firstly, OptimLUM runs for the darkest conditions of the spaces as noted above. Then, windows are designed for these three rooms with different sizes to observe their daylight conditions and the number of luminaires required to be used during the day within. The calculation process of illuminance with daylight and their results will be presented. Afterwards, resulting layouts with the integration of daylight and artificial lighting will be mentioned.

5.3.1. Daylight Factor Calculation

The daylight factor at a point is calculated based on its three components which are the sky component SC, the externally reflected component ERC and the internally reflected component IRC (Figure 5.12).

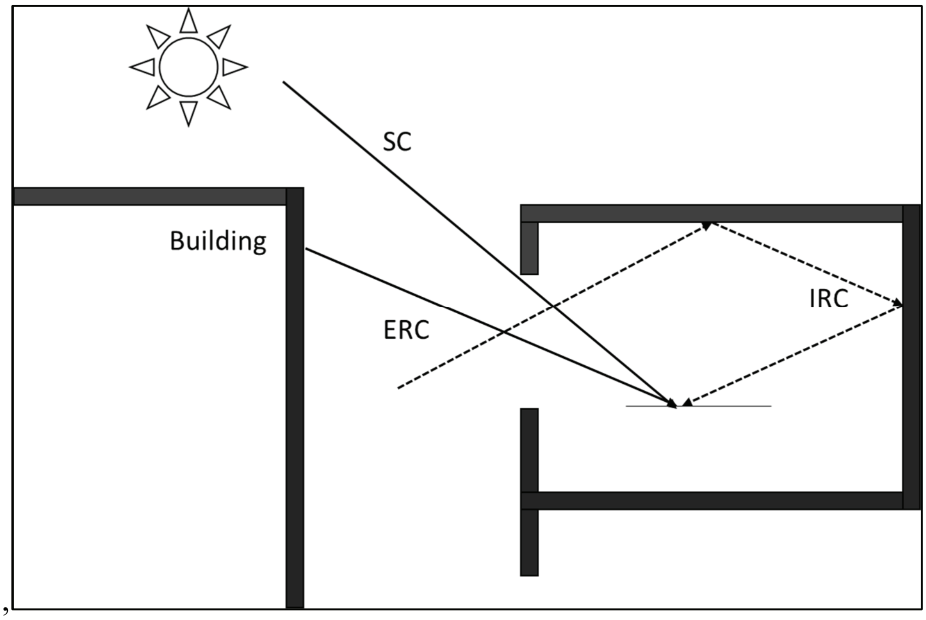


Figure 5.12. Diagram of three daylight factor components.

The SC and ERC can be determined by the BRE daylight protractors which are applied to dimensions of room and windows. The most commonly used method for determining the IRC is based on the BRE split-flux formula. The BRS method was developed by the Building Research Establishment, or BRE as a relatively simple and graphic method of calculating the DF components (CIBSE 1999). The basic needs to read the table are;

- The height of working plane above floor,
- W1, W2, the effective widths of the window on each side of a line drawn from the reference point normal to the plane of the window;
- D, the distance from the reference point to the plane of the window.

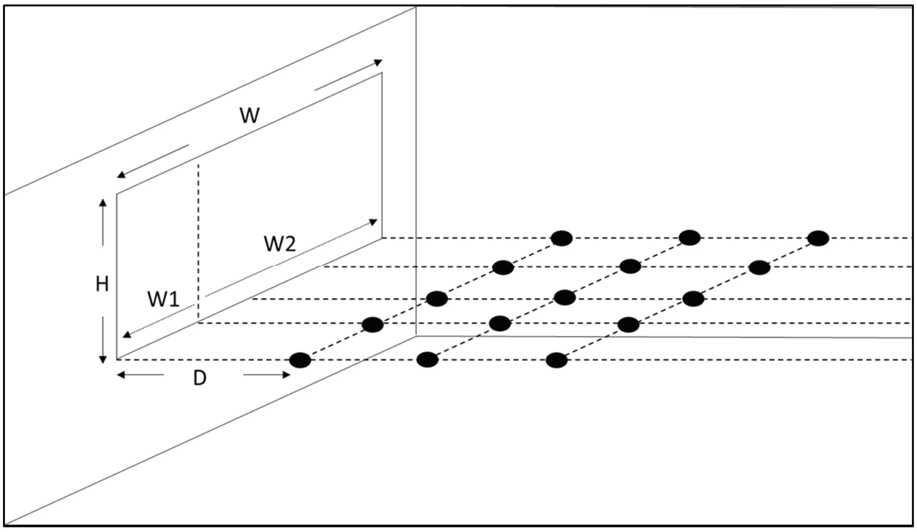


Figure 5.13. Diagram of information about room, window and reference points for SC calculation.

Based on this needed information about room and window, a window is created with different dimensions for each small, medium and large rooms. Left and right edges of the windows are at least 0.4m away from walls. The upper part of the windows is 0.4m below from ceiling. To not block the direct sunlight on the reference points, the created window sill for this study is at the same level with the working plane. Reference points to calculate daylight factor are the same reference points of OptimLUM. According to these, width of window for small room is 4 m and its height is 1.8 m. width of window for the middle room is 7.2 m and for large room it is 9.2 m. all of the windows height is 1.8 m due the same ceiling level. SC value can be read from the Table 5.28 based on the ratios H/D1, W1/D1 and W2/D1. Sky component at any other reference point was found by addition or subtraction of these values.

To calculate internally reflected component (IRC) by BRC table (Table 5.29), the ratio of glazed area to floor area and room surface reflectance values are required. To analyze the energy efficient layouts of model, r_{wall} is defined as 0.6, r_{ceil} is 0.7 and r_{floor} is 0.2. According to these information. C_{rf} is 1 and C_{avg} is 1.3 for this calculation.

Table 5.28. SC values based on Ratio of W/D and H/D.

	Ratio W/D											
	0	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.2**	**1.4**	**1.6**	**2**	**2.4**	**0**	
	0.1	0.02	0.03	0.04	0.05	0.05	0.06	0.06	0.06	0.07	0.08	**8**	
	0.2	0.06	0.11	0.14	0.2	0.21	0.22	0.22	0.22	0.23	0.24	**11**	
	0.3	0.14	0.26	0.34	0.42	0.47	0.49	0.5	0.5	0.51	0.53	**17**	
	0.4	0.25	0.45	0.62	0.75	0.89	0.92	0.95	0.95	0.96	0.98	**22**	
	0.5	0.39	0.7	0.97	1.1	1.3	1.4	1.4	1.4	1.5	1.5	**27**	
	0.6	0.53	0.98	1.3	1.6	1.8	1.9	1.9	2	2	2.1	**31**	
	0.7	0.68	1.3	1.7	2.1	2.3	2.5	2.5	2.6	2.6	2.8	**35**	
	0.8	0.83	1.6	2.2	2.6	2.9	3.1	3.2	3.3	3.3	3.1	**30**	
	0.9	0.99	1.9	2.6	3.1	3.4	3.7	3.8	3.9	4	4.2	**42**	
	1	1.1	2.2	3	3.6	4	4.3	4.5	4.6	4.7	5	**45**	
	1.1	1.3	2.5	3.4	4.1	4.6	4.9	5.1	5.3	5.4	5.7	**48**	
	1.2	1.4	2.7	3.8	4.5	5	5.4	5.7	5.9	6.1	6.3	**50**	
	1.3	1.5	2.9	4.1	4.9	5.5	5.9	6.2	6.4	6.7	7	**52**	
Ratio H/D	**1.4**	1.6	3.2	4.4	5.2	5.9	6.4	6.7	7	7.3	7.6	**54**	**Angle of obstruction**
	1.5	1.7	3.3	4.6	5.6	6.2	6.8	7.1	7.4	7.8	8.1	**56**	
	1.6	1.8	3.5	4.9	5.8	6.5	7.2	7.5	7.8	8.2	8.6	**58**	
	1.7	1.9	3.6	5.1	6.1	6.8	7.5	7.8	8.2	8.6	9.1	**60**	
	1.8	1.9	3.8	5.3	6.3	7.1	7.8	8.2	8.5	9	9.5	**61**	
	1.9	2	3.9	5.4	6.5	7.3	8.1	8.5	8.8	9.4	9.9	**62**	
	2	2	4	5.6	6.7	7.5	8.3	8.7	9.1	9.7	10.3	**63**	
	2.1	2.1	4.1	5.8	7	7.9	8.7	9.1	9.6	10.2	10.9	**66**	
	2.2	2.2	4.3	6	7.3	8.1	9.1	9.5	10	10.7	11.5	**67**	
	2.3	2.2	4.4	6.2	7.5	8.4	9.3	9.8	10.2	11.1	11.9	**69**	
	2.4	2.3	4.5	6.3	7.6	8.6	9.6	10	10.5	11.4	12.3	**70**	
	2.5	2.3	4.5	6.4	7.8	8.7	9.8	10.2	10.7	11.7	12.7	**72**	
	2.6	2.4	4.6	6.6	8	9	10.1	10.6	11.1	12.2	13.3	**74**	
	2.7	2.4	4.7	6.7	8.2	9.2	10.3	10.9	11.4	12.4	13.7	**76**	
	2.8	2.4	4.8	6.8	8.3	9.4	10.5	11.1	11.7	12.7	14.2	**79**	
	3	2.5	4.9	6.9	8.4	9.6	10.7	11.6	12.2	13	15	**90**	

Table 5.29. Minimum IRC values for 0.7 r_{ceil}, 0.2 r_{floor}, 0.6 r_{wall}.

Ratio of glass area/ floor area	Glass area as a % of floor area	Rc:0.7 Rf:0.2 Rw:0.6
1:50	2	0.1
1:20	5	0.3
1:14	7	0.4
1:10	10	0.6
1:6.7	15	0.8
1:5	20	1.1
1:4	25	1.3
1:3.3	30	1.5
1:2.9	35	1.8
1:2.5	40	2
1:2.2	45	2.2
1:2	50	2.3

Considering ratio of total glass area to floor area, IRC_{min} is established by the table and IRC_{avg} is calculated for each room by multiplying IRC_{min} , C_{rf} and C_{avg}.

$$IRC_{avg} = IRC_{min} \times C_{rf} \times C_{avg} \tag{5.14}$$

The externally reflected component (ERC) is decided as 0.2 for this study because this is an estimate that represents the average reflectance of common building materials and natural surfaces. Finally, daylight factor of a point in room can be calculated by adding of three components.

$$DF = DF^{SC} + DF^{ERC} + DF^{IRC} \tag{5.15}$$

Daylight factor was defined as the ratio of the internal horizontal illuminance (E_{in}) at a point in a space to the unobstructed external horizontal illuminance (E_{ext}). Light from the sky can arrive at a point in a space directly if any sky is visible from that point, and also indirectly following one or more reflections from surfaces inside and outside of the space. The daylight factor is generally expressed as a percentage:

$$DF = \frac{E_{in}}{E_{ext}} 100 \tag{5.16}$$

E_{in}: internal illuminance at fixed point

E_{ext}: external horizontal illuminance under an overcast or uniform sky

5.3.2. Energy Efficient Luminaire Layouts with Daylight

To estimate internal illuminance at reference points, it is needed to know E_{ext}. E_{ext} for this study, it is accepted as 19.400 lux according to latitude of İzmir which is 38.42° (Mardaljevic and Christoffersen 2017). E_{in} for each reference point is calculated according to daylight factor calculation with components and E_{ext}. E_{in} values under 500 lux which are insufficient for lighting are illustrated with blue color in

Figure 5.14, The window in the small room is sufficient to provide satisfactory lighting. While the window for middle room is lightening approximately half of the room as seen in Figure 5.16, a small part of the large room has access to be lightened with daylight Figure 5.17.

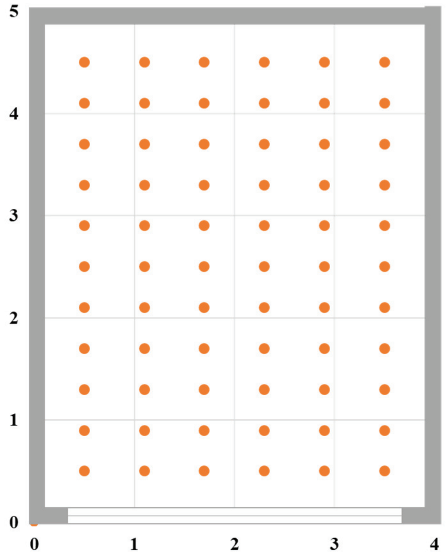


Figure 5.14. Daylight illuminance of small room.

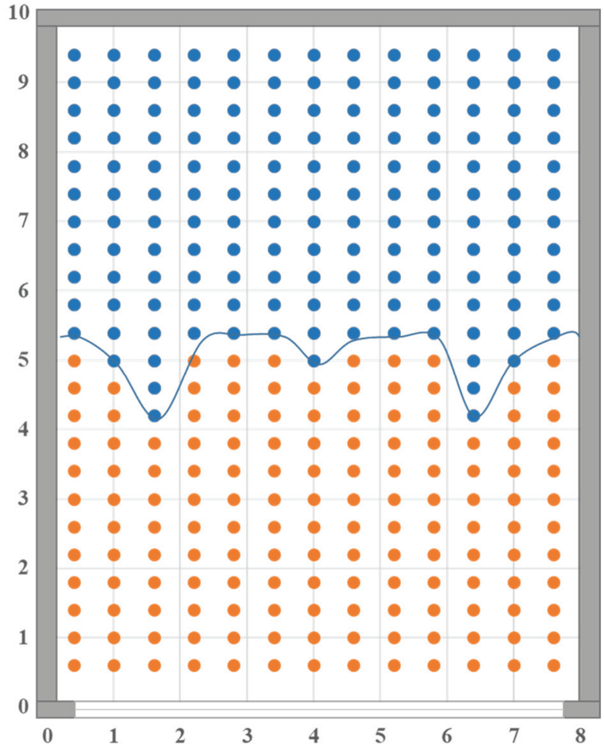


Figure 5.15. Daylight illuminance of medium room.

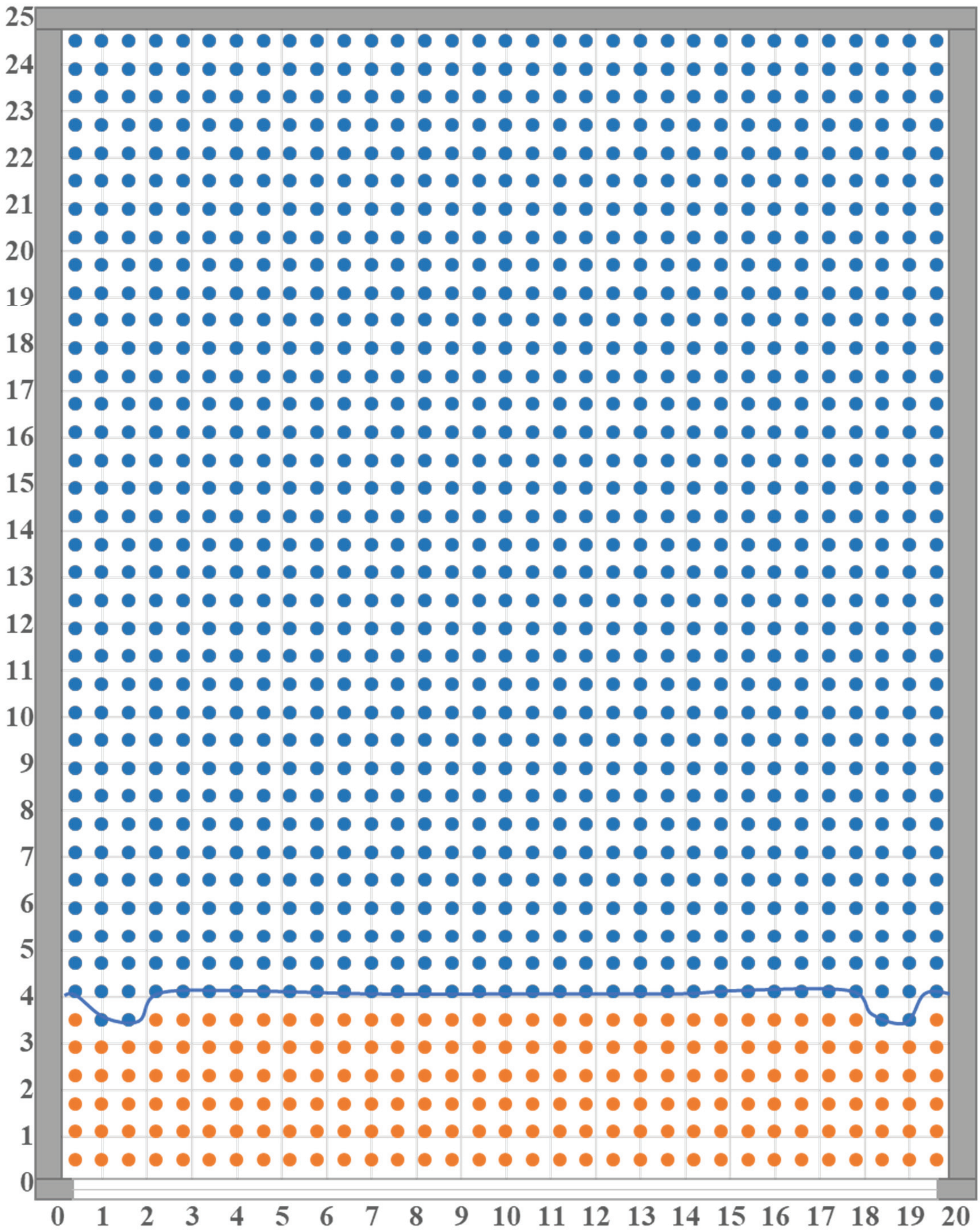


Figure 5.16. Daylight illuminance of large room.

Energy efficient layouts of three room sizes with 14 different luminaires are matched with daylight outputs to observe the number of luminaires required to be used during the day. While it is not required to switch on any luminaire at the small room, there are different layouts with different types of luminaires for medium room. All reference points are intended to be at least 500 lux by respectively switching off the luminaires which are close to the window. In the layouts with luminaires 1, 2,4,10 and 13, using only the luminaires which are located on the area that daylight could not adequately illuminate gives satisfied illuminance like Figure 5.17 while switching on only one luminaire below the daylighting line is sufficient in the layouts of luminaires 7, 8, 9 and 14, more than one luminaire is needed in the layouts with luminaires 3, 5, 6, 11 and 12.

Differently other results, different layouts are obtained with luminaire number 11. 8 of luminaire numbered 11 is sufficient for E_{avg} for darkest conditions. However, 8 luminaires are expected to operate throughout the day. When OptimLUM runs for 9 of luminaires numbered 11, switching on only 4 luminaires provide satisfactory illuminance (Figure 5.18).

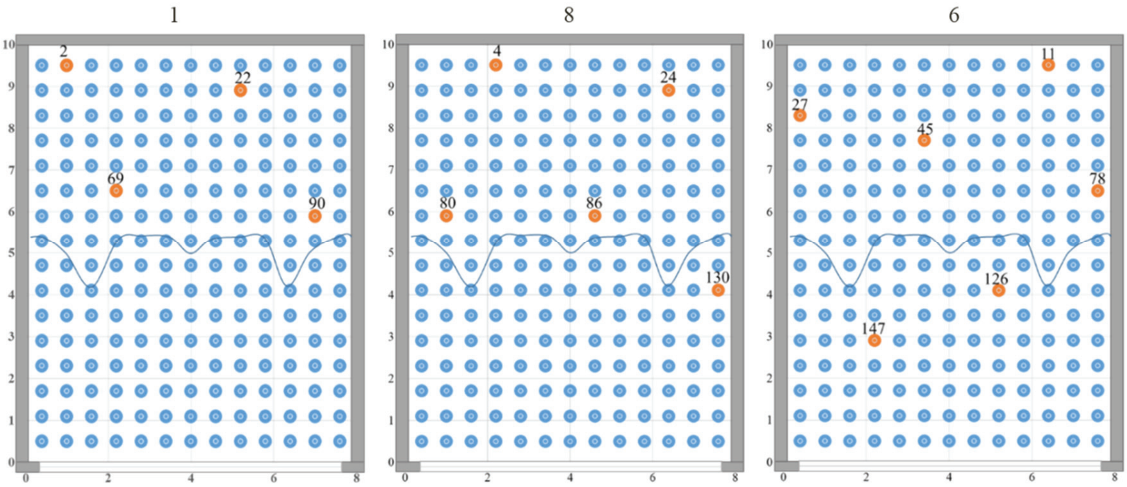


Figure 5.17. OptimLUM layouts and daylight integration with luminaires 1, 8 and 6 for medium room.

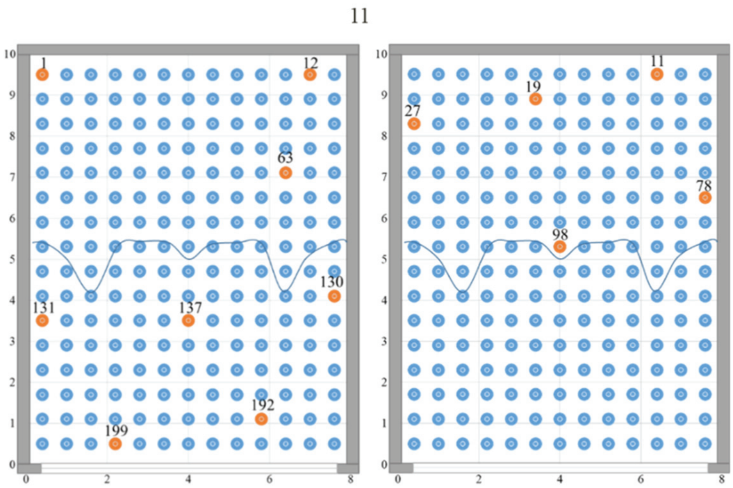


Figure 5.18. OptimLUM layouts and daylight integration with eight and nine of luminaires 11 for medium room.

Table 5.30 shows the obligatory number of luminaire for darkest conditions and daylight integration of medium room to make OptimLUM user choose based on his/her significance.

Table 5.30. General information about luminaires and their results based on OptimLUM estimation with daylight integration for medium room.

MEDIUM ROOM					
LUMINAIRE	**#**	**LP**	**# DL**	**U**	**LPD**
1	8	42 W	4	0.15	4.2 W/m^2
2	10	69.5 W	4	0.10	8.68 W/m^2
3	8	30 W	6	0.29	3 W/m^2
	9		5	0.19	3.37 W/m^2
4	14	19 W	7	0.12	3.32 W/m^2
5	14	17.3 W	9	0.15	3.02 W/m^2
6	8	30.4 W	6	0.18	3.04 W/m^2
7	7	37.5 W	5	0.17	3.28 W/m^2
8	8	28 W	5	0.27	2.8 W/m^2
	9		5	0.19	3.15 W/m^2
9	12	20 W	7	0.12	3 W/m^2
10	8	26.7 W	4	0.11	2.67 W/m^2
11	8	25W	8	0.29	2.5 W/m^2
	9		5	0.14	2.81 W/m^2
12	13	19W	9	0.15	3.08 W/m^2
13	8	37 W	4	0.13	3.7 W/m^2
14	8	34 W	5	0.16	3.4 W/m^2

CHAPTER 6

DISCUSSION

According to the findings of the validation, the progression and the final phases of OptimLUM mentioned in previous chapters, there are some discussions based on objectives of this study and in the light of the relevant literature.

6.1. Validation Process and Progression of OptimLUM

The chapter 4 presented the development and the validation processes of a new optimization model named OptimLUM to find the optimum position for luminaires providing energy efficient layout.

In an earlier study (Shikder, Mourshed, and Price 2010) researchers aimed to find optimum positions for two different luminaires in two identified and smaller/limited areas. Apart from this study, OptimLUM focused on finding the optimum positions of more than one luminaire in one identified and determinate area. Also, OptimLUM is flexible for different room sizes because its horizontal and vertical grids are encoded in VBA. Thus, the mutual impact of all positioned luminaires while calculating the illuminance and uniformity are integrated in the optimization model. The optimization model in this case performs well in locating and determining the luminaire positions. There can be also seen in literature that similar studies about lighting and optimization that they have created complicated, non-dynamic model.

Based on illuminance distributions for all scenarios that includes OptimLUM estimation and alternative layouts, OptimLUM illuminance outputs are closer to the actual measurements when compared with DIALux outputs. Model outputs are more accurate than a simulation program by comparing illuminance measurements.

Being energy efficient lighting is based on using the minimum number of luminaires which means minimum usage of luminaire power in the best possible layout design. Unlike common lighting design solutions; all luminaires should be the same and be placed equally apart from each other with same orientation, OptimLUM offers unsymmetrical but more energy efficient layouts.

As Rocha et al. 2016 mentioned that lighting designers try to offer the best solution to a given lighting design problem and accordingly, they deals with the a multi-objective problem. Heuristics are the widely used method to solve such kind of problems but they are not widely applied on lighting design (Rabaza et al. 2013). Like Rocha's study, the argument of this study is to solve the problem including multiple criteria by using heuristics and considering low energy consumption and better illumination quality. OptimLUM uses Evolver optimization program which includes heuristics. To provide uniform illumination on work plane, it is widely used formula is the rate of the minimum by the average of illuminance values. Differently from this common usage, Ferentinos and Albright 2005 used Mean Radiant Deviation to understand differentiation of illuminance values in the whole space. Two formulas are used separately for OptimLUM to observe differences of their results. The findings from progression of OptimLUM demonstrate that minimizing MRD formula is a better solution than maximizing uniformity formula (E_{min}/E_{avg}) with minimum higher illuminance values on walls of MRD.

Before designing a luminaire layout for an office, reflectance values of horizontal and vertical planes of the room is an architectural metric that must be taken into consideration. While upgrading the OptimLUM constraints, due to low reflectance value of walls, luminance cannot get value over 50. According to CIBSE/SLL 2002 recommendation of about luminance for walls of offices, luminance of walls should be between 50-150 cd/m^2. Even though OptimLUM is a flexible model to considerate reflectance value for calculation process, designers must be careful in selecting materials based on some recommendations about surface reflectance values. Ceiling should be 0.7 or above, walls should be between 0.5-0.7 and floors between 0.1-0.3 (Philips Lighting B.V. 1993).

6.2. Energy Efficient OptimLUM Layouts

For different room sizes, the conducted layouts by OptimLUM generally follow the common sense of located more luminaires at the edges of the room and less luminaires towards the middle of the area unlike common proposed lighting design solutions. Accordingly, there may be some values that are higher than expected. But these calculation points are located very close to luminaires. They are ignored due to not being in the visual field of users.

According to the layouts mentioned above, layout with fluorescent luminaires shows a better uniform illumination performance than layouts with LED. But this type of luminaires is not energy efficient due to high wattage. Luminaire numbered 10 which is a mounted LED luminaire illustrates a closer uniform lighting performance to fluorescent luminaire. Besides, it consumes less energy per square meter. This may be a proof of technological developments in luminaires will lead well-designed lighting. For estimation of layouts with two similar downlight types, OptimLUM locates similarly high number of downlight luminaires but these layouts give good solutions for uniform lighting with less LPD. The similar uniformity can be obtained by placing more luminaires with narrow angles than other types of luminaires.

6.3. Energy efficiency with Daylight Integration

OptimLUM layouts of different room sizes with 14 different luminaires are matched with daylight outputs to decrease the number of luminaires required during the day. While it is not required to switch on any luminaire at the small room, there are different layouts with different types of luminaires for medium room. All reference points are intended to be at least 500 lux by respectively switching off the luminaires which are close to the window. During the day time, mostly using only the luminaires which are located on the area that daylight could not adequately illuminate gives satisfied illuminance. However, according to layouts of luminaires that cannot provide a good uniform lighting, all luminaires should be switch on also during the day. When uniformity output is not close to zero, increasing the number of luminaire will help OptimLUM make better estimation. By considering darkest conditions and daylight integration, more energy efficient layout can be obtained like outputs of luminaire 11.

CHAPTER 7

CONCLUSION

This study aims to estimate the most accurate locations, number and type of light sources in offices according to visual comfort conditions and energy efficicency by proposing a mathematical model. Before this model extented its final case, it has gone several phases. Firstly, illuminance calculation method was decided and conducted. It was tested with a preliminary case. Then, OptimLUM was developed and encoded on VBA. This developed phase was validated by comparing measurements and simulations. According to this validation step, the model was progressed again with the new constraints. As a final, there are some energy efficient layouts for different office sizes with different number and type of light sources. To be more energy efficient and decrease the energy loads by artificial lighting, these layouts were integrated with daylight.

Considering the validity of the OptimLUM outputs, instead of using simulation tools, this proposed model can be used by the architect or lighting designer to determine the correct position of the luminaire to avoid unbalanced illuminance distribution while selecting the accurate light source for offices. Although simulation tools about lighting are helpful for designers, they have to randomly simulate more than one layouts to provide lighting design parameters for one model. OptimLUM guide the users about these parameters by providing uniform illumination on work plane with the constraints about vertical illuminances and luminance values. By employing OptimLUM, combinations of different design (layout, lamp and luminaire selection) alternatives can be tested together in one office according to these defined comfort and efficiency constraints. OptimLUM provides design solutions with the inclusion of maximizing comfort conditions, and minimizing the energy consumption of the lighting scheme. This model will also be useful in energy saving decisions of lighting design by locating the minimum number of lamps with the required and uniform illuminance.

Considering the mentioned guidance of OptimLUM about lighting constraints, OptimLUM would be also a knowledge-based tool to help non expert users to decide on the locations and number of luminaires for offices. Regarding the flexibility to change the constraints of OptimLUM, the model would be a design aid tool for experts while they propose energy efficient lighting layouts not only for offices but also different type of spaces.

According to literature, this proposed tool is a new alternative approach of applying an optimization model to architectural lighting research due to the achievement of OptimLUM about finding optimum positions of more than one luminaire in one identified area, its flexibility for different room dimensions, including different uniformity formula and constraints about vertical and horizontal surfaces.

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APPENDIX A

STATISTICAL EVALUATION OF MEASUREMENTS, SIMULATION AND OptimLUM CALCULATION

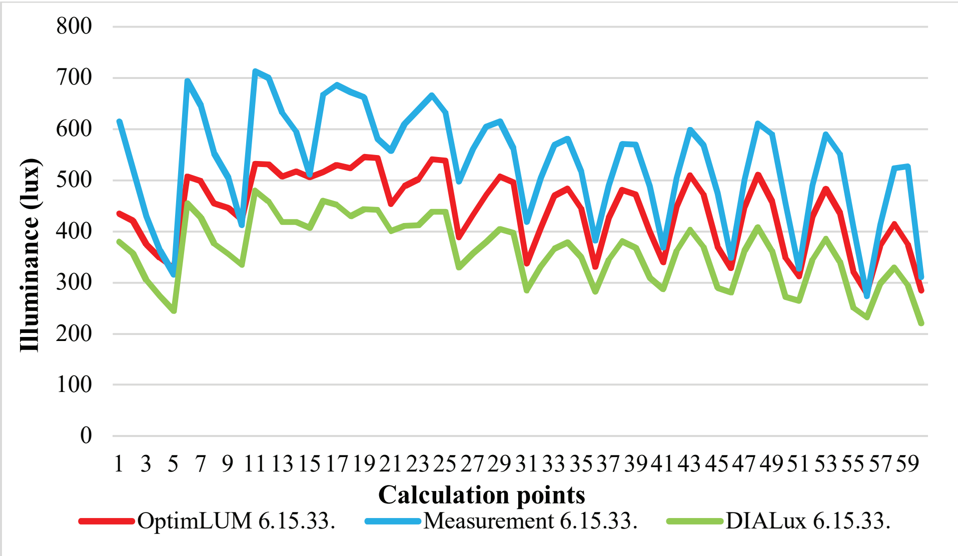


Figure A.1. Distributions of illuminance values in OptimLUM layout (6.15.33.) for LED luminaire.

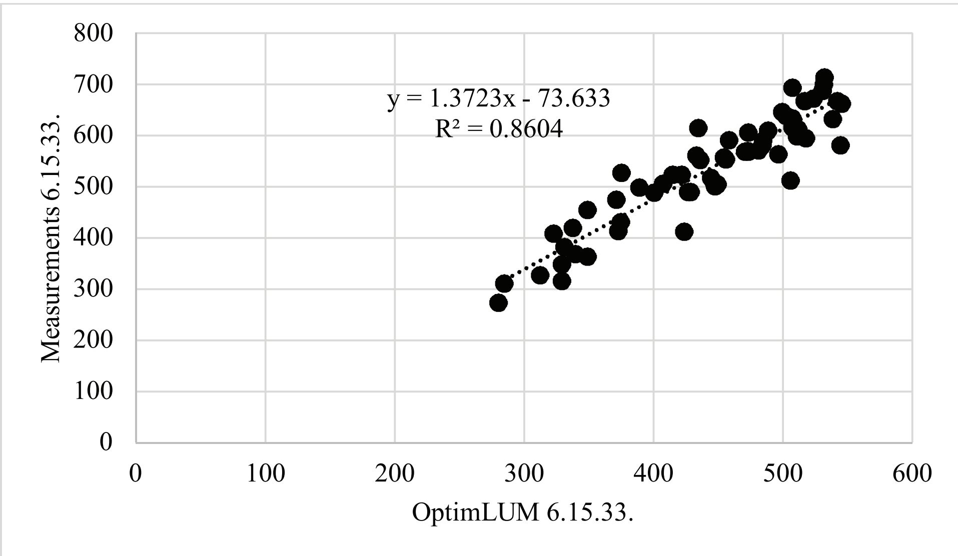


Figure A.2. Scatter diagram of OptimLUM layout (6.15.) for LED luminaire.

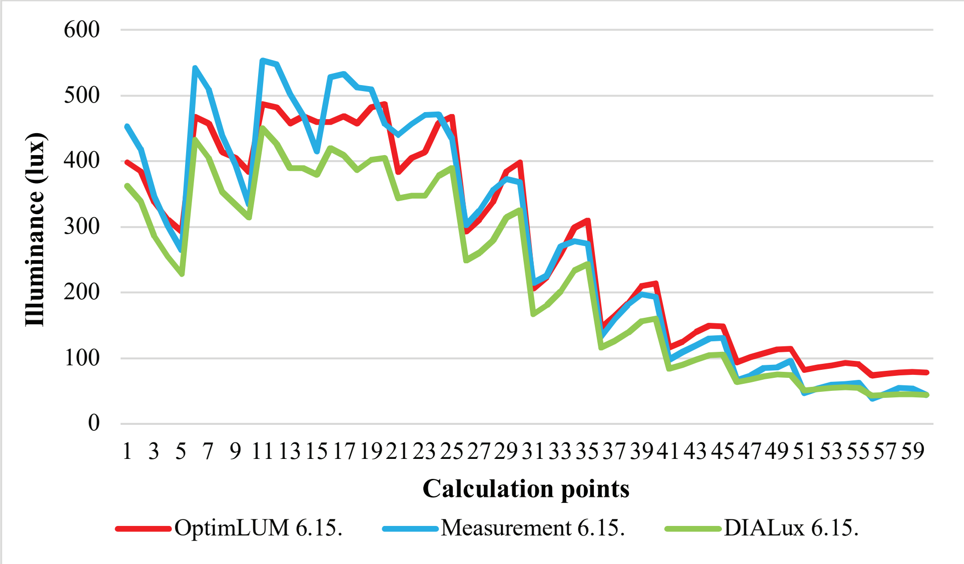


Figure A.3. Distributions of illuminance values in double configuration of OptimLUM layout (6.15.) for LED luminaire.

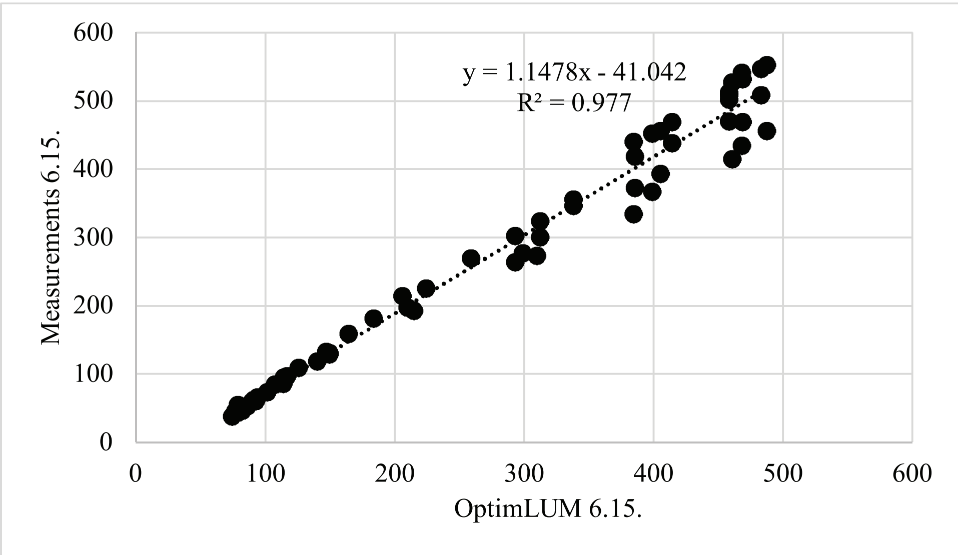


Figure A.4. Scatter diagram of double configuration of OptimLUM layout (6.15.) for LED luminaire.

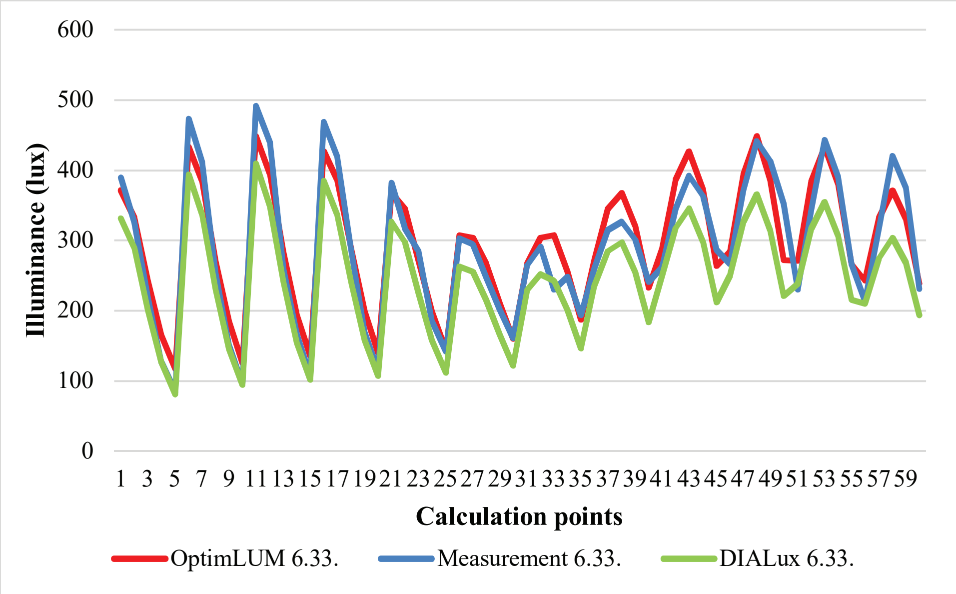


Figure A.5. Distributions of illuminance values in double configuration of OptimLUM layout (6.33.) for LED luminaire.

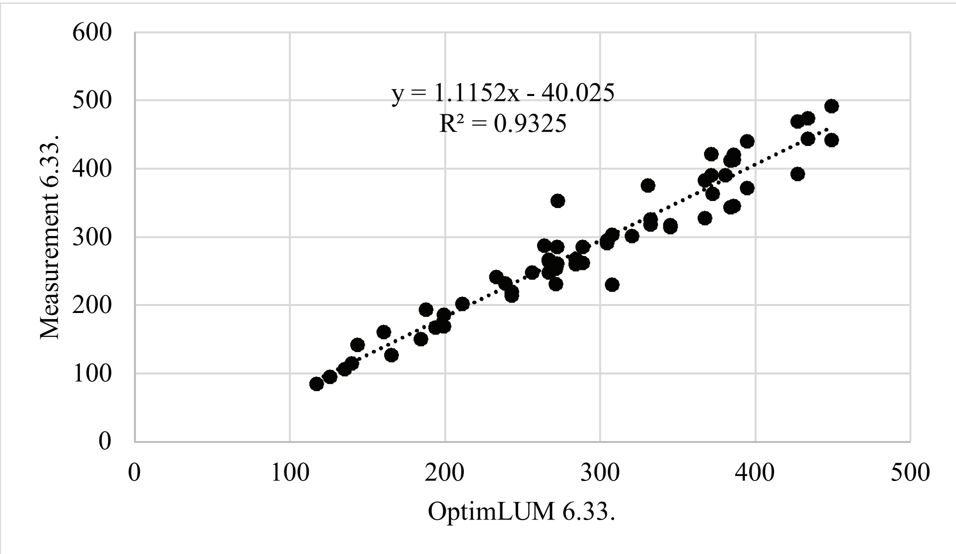


Figure.A.6. Scatter diagram of double configuration of OptimLUM layout (6.33.) for LED luminaire.

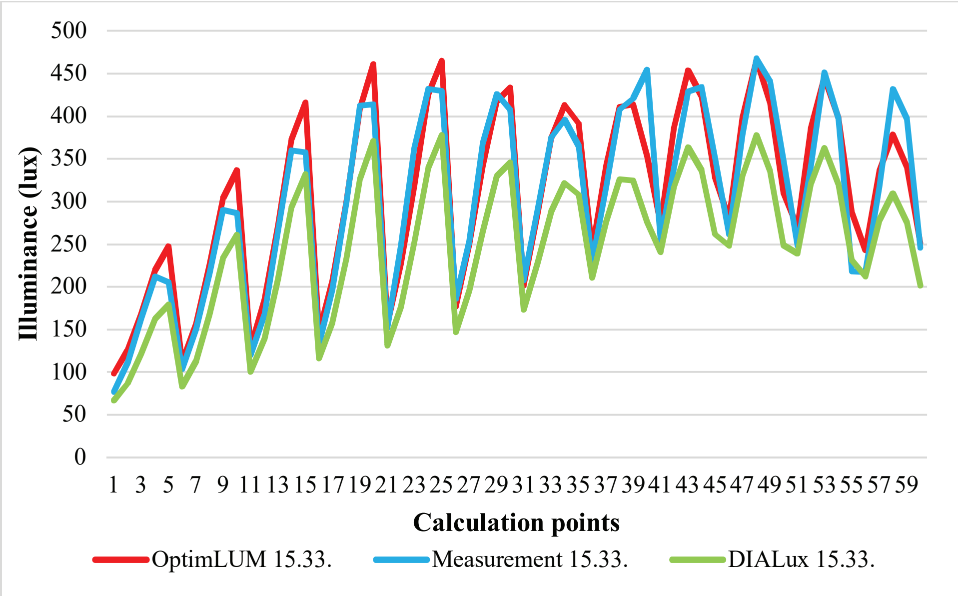


Figure A.7. Distributions of illuminance values in double configuration of OptimLUM layout (15.33.) for LED luminaire.

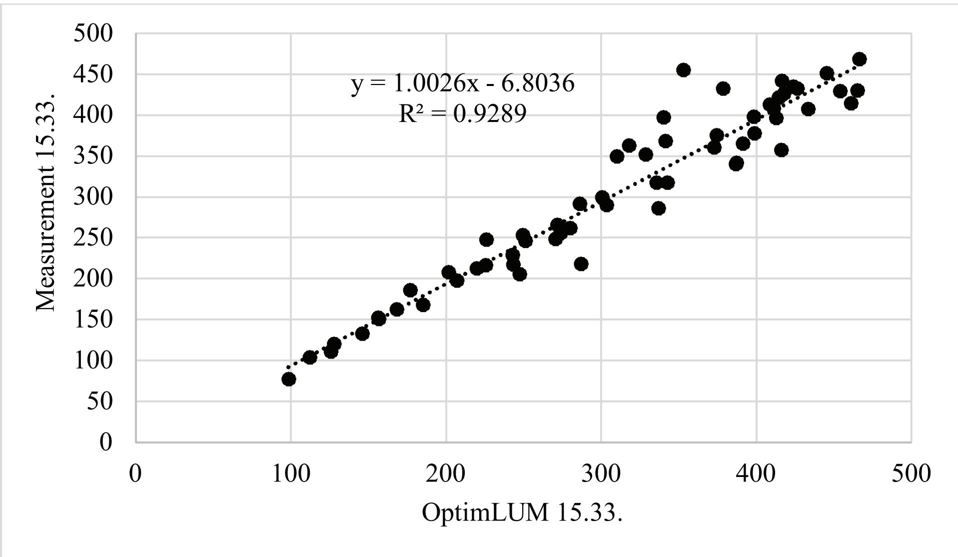


Figure A.8. Scatter diagram of double configuration of OptimLUM layout (15.33.) for LED luminaire.

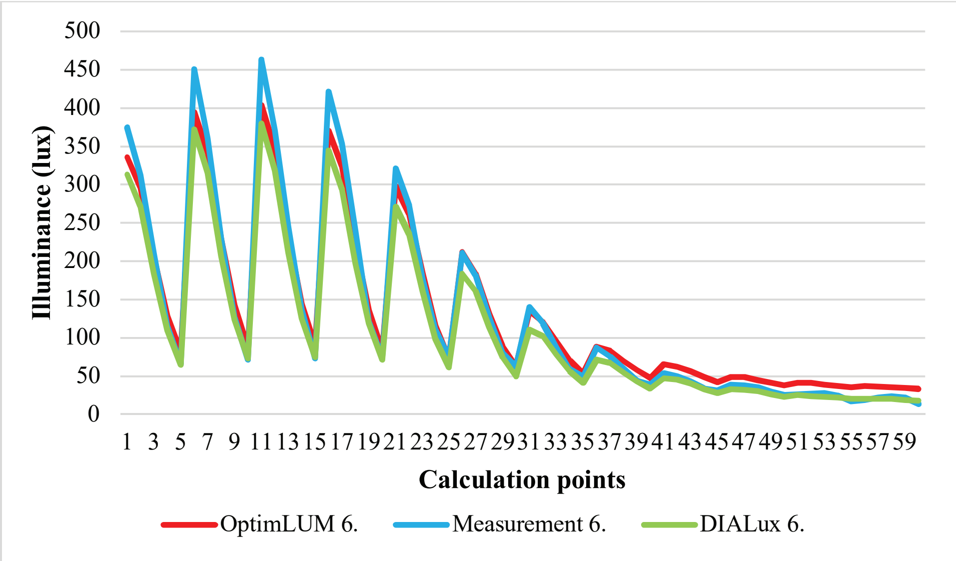


Figure A.9. Distributions of illuminance values in single configuration of OptimLUM layout (6) for LED luminaire.

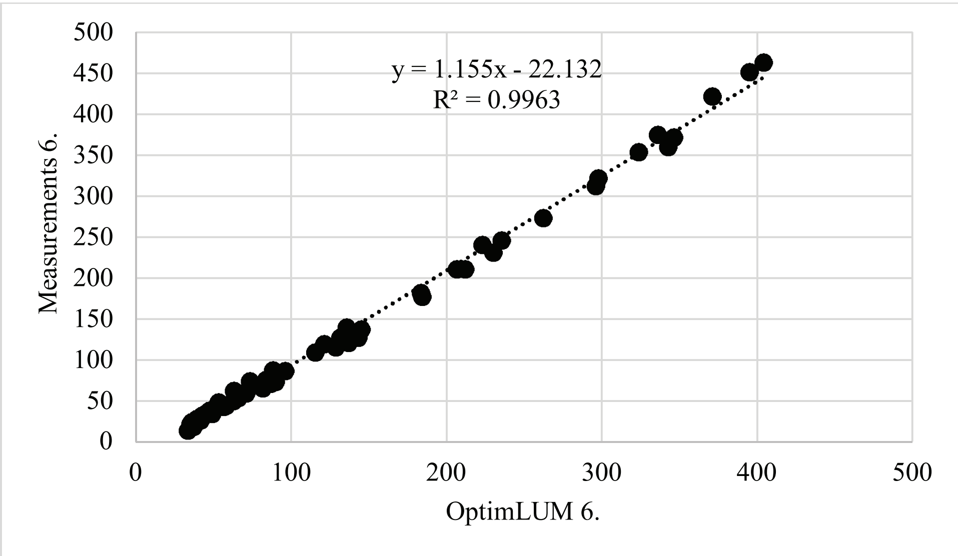


Figure A.10. Scatter diagram of single configuration of OptimLUM layout (6) for LED luminaire.

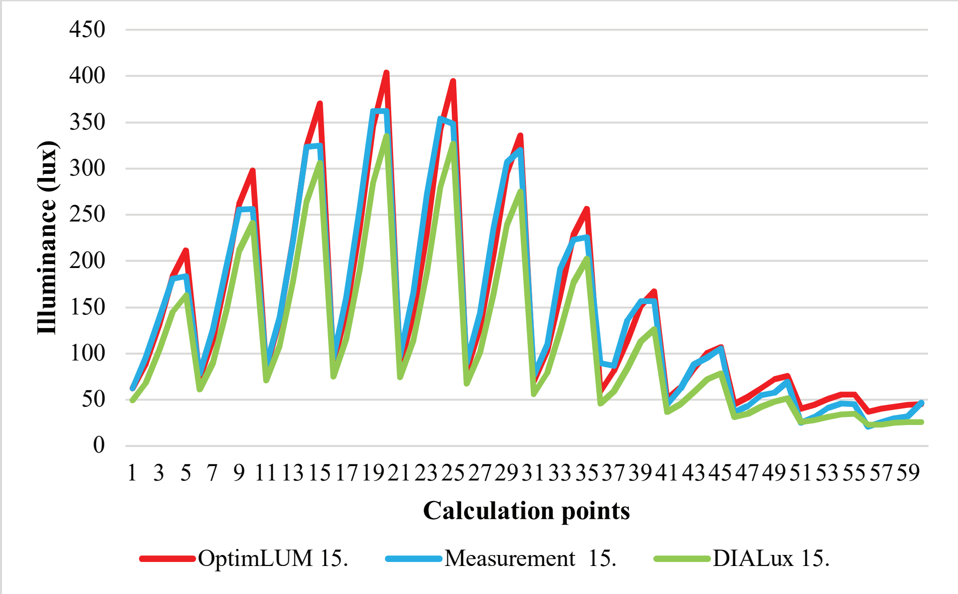


Figure A.11. Distributions of illuminance values in single configuration of OptimLUM layout (15) for LED luminaire.

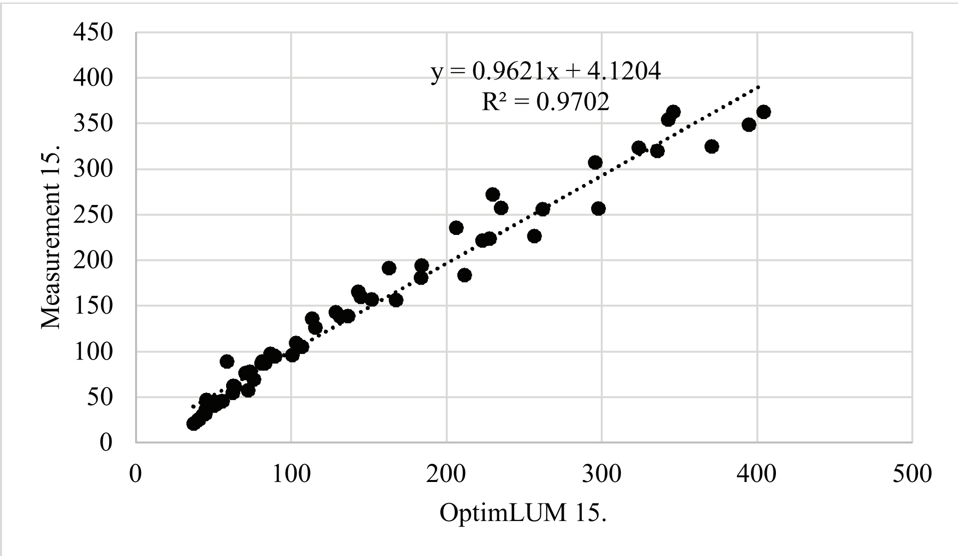


Figure A.12. Scatter diagram of single configuration of OptimLUM layout (15) for LED luminaire.

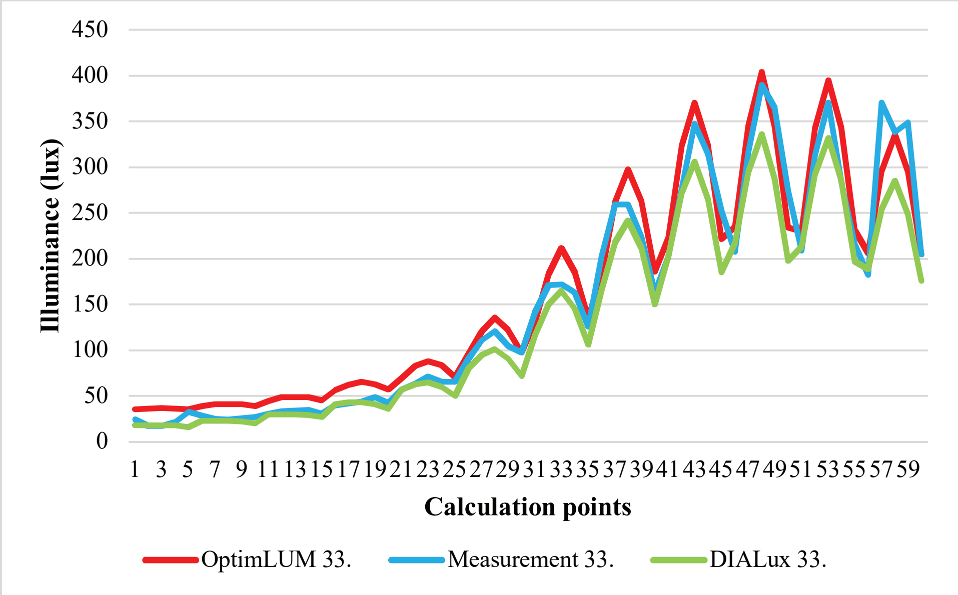


Figure A.13. Distributions of illuminance values in single configuration of OptimLUM layout (33) for LED luminaire.

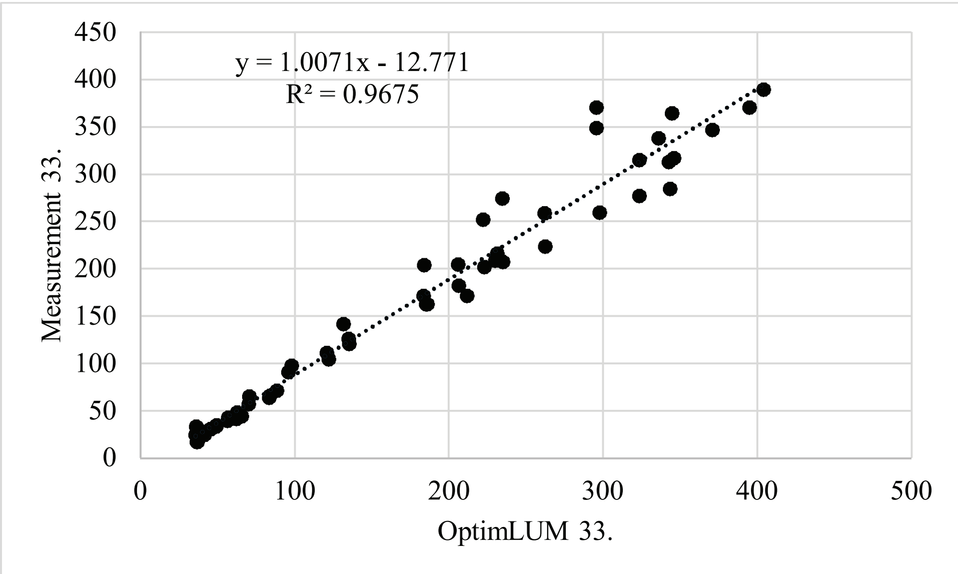


Figure A.14 Scatter diagram of single configuration of OptimLUM layout (33) for LED luminaire.

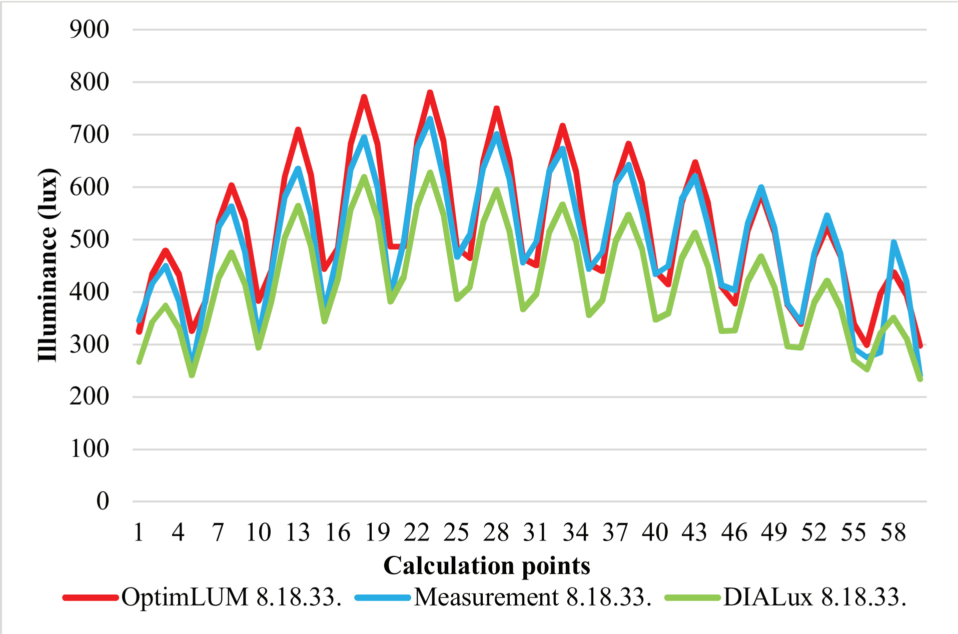


Figure A.15. Distributions of illuminance values Alternative I layout (8.18.33) for LED luminaire.

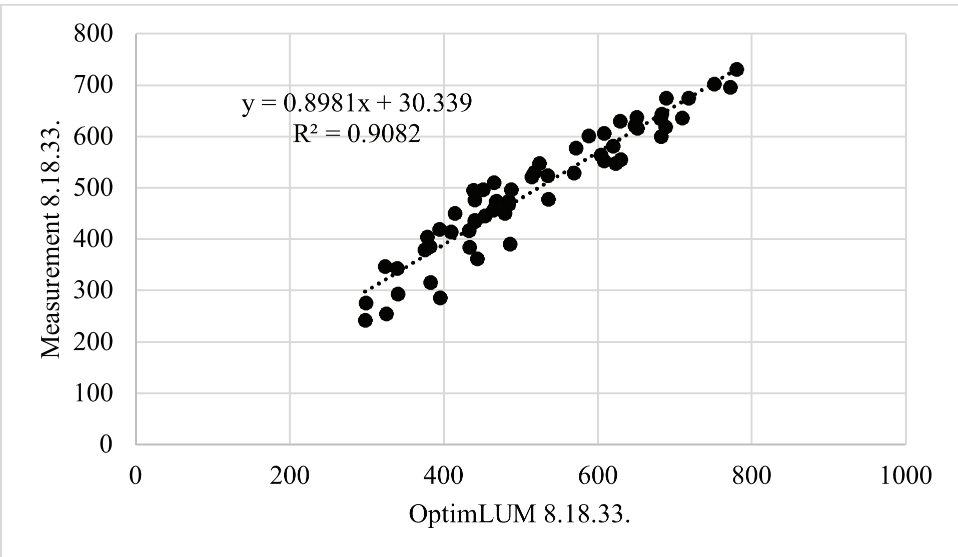


Figure A.16. Scatter diagram of Alternative I layout (8.18.33) for LED luminaire.

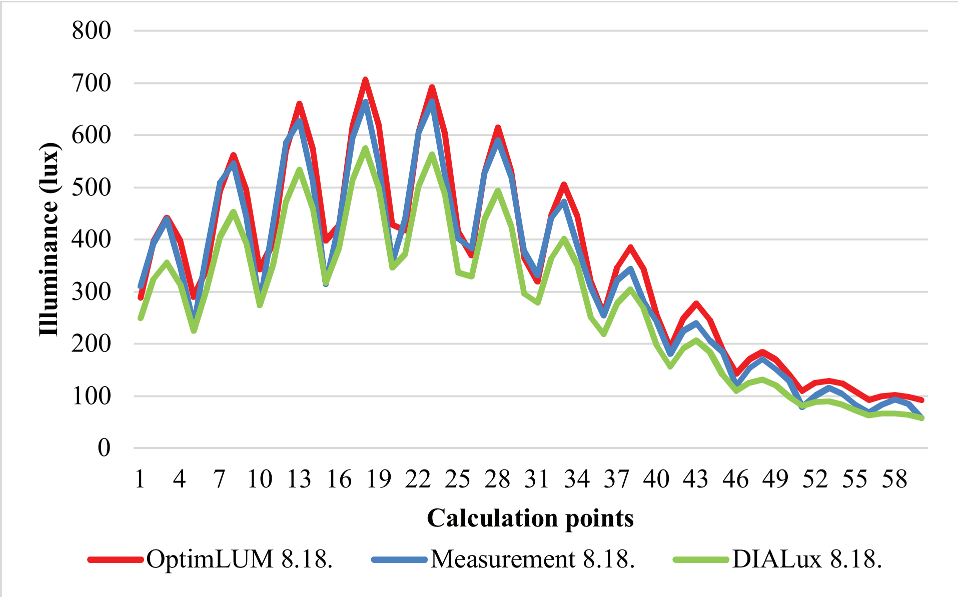


Figure A.17. Distributions of illuminance values in double configuration of Alternative I layout (8.18) for LED luminaire.

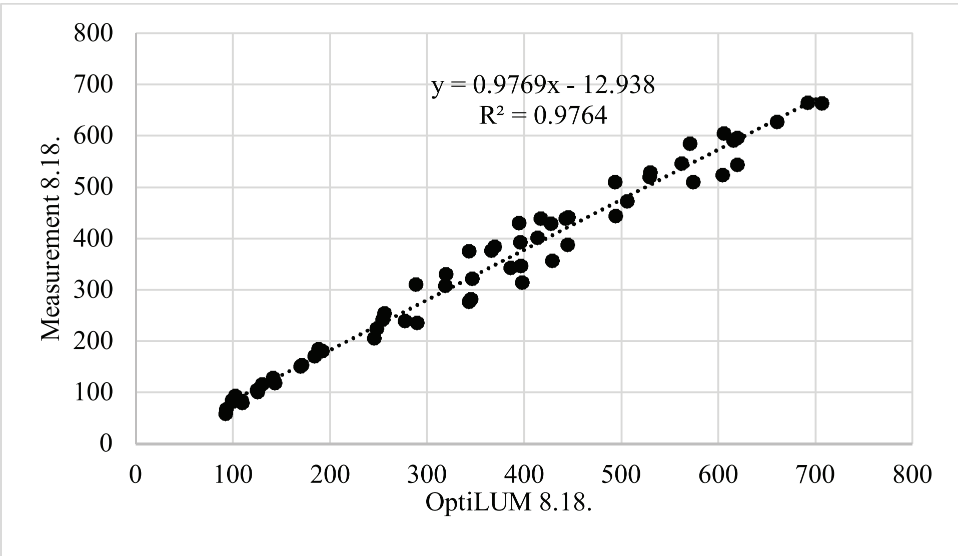


Figure A.18. Scatter diagram of double configuration of Alternative I layout (8.18) for LED luminaire.

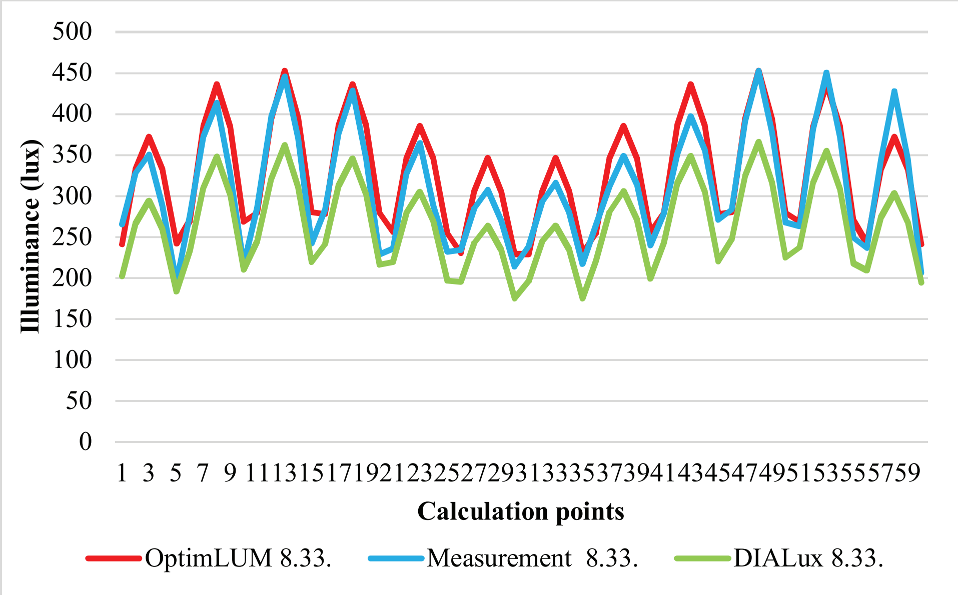


Figure A.19. Distributions of illuminance values in double configuration of Alternative I layout (8.33) for LED luminaire.

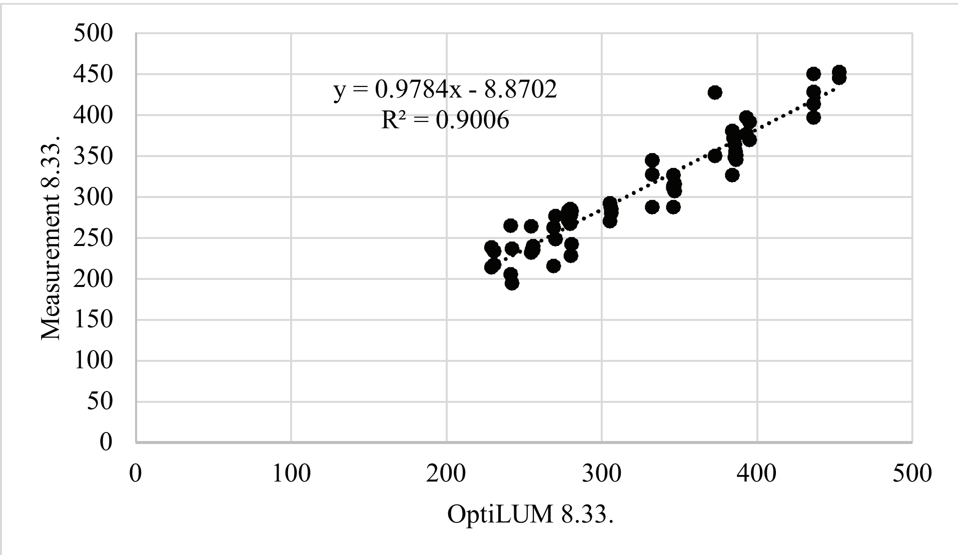


Figure A.20. Scatter diagram of double configuration of Alternative I layout (8.33) for LED luminaire.

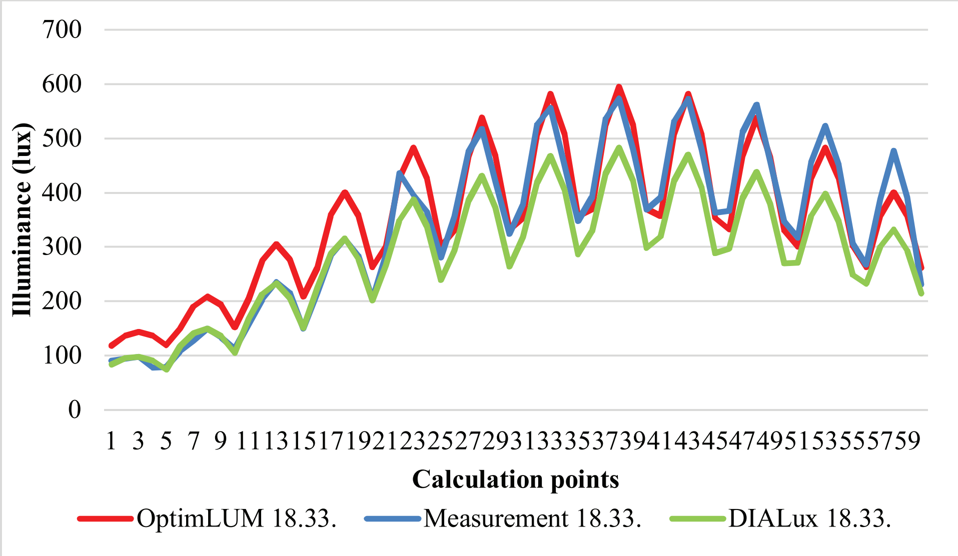


Figure A.21. Distributions of illuminance values in double configuration of Alternative I layout (18.33) for LED luminaire.

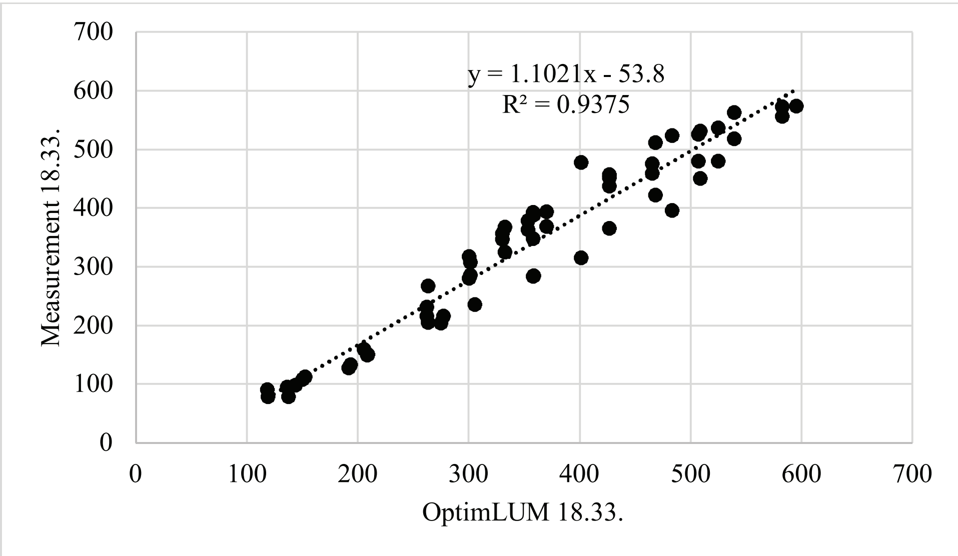


Figure A.22. Scatter diagram of double configuration of Alternative I layout (18.33.) for LED luminaire.

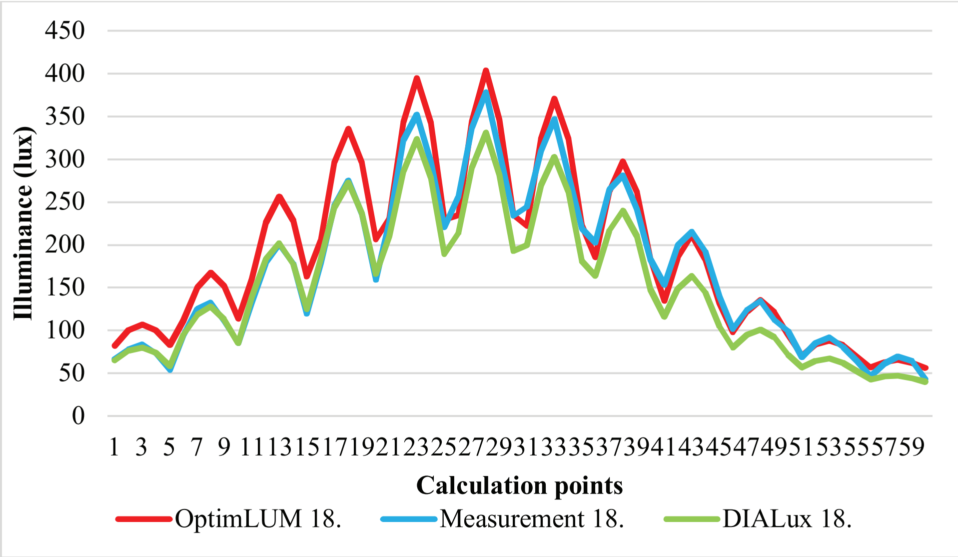


Figure A.23. Distributions of illuminance values in single configuration of Alternative I layout (18) for LED luminaire.

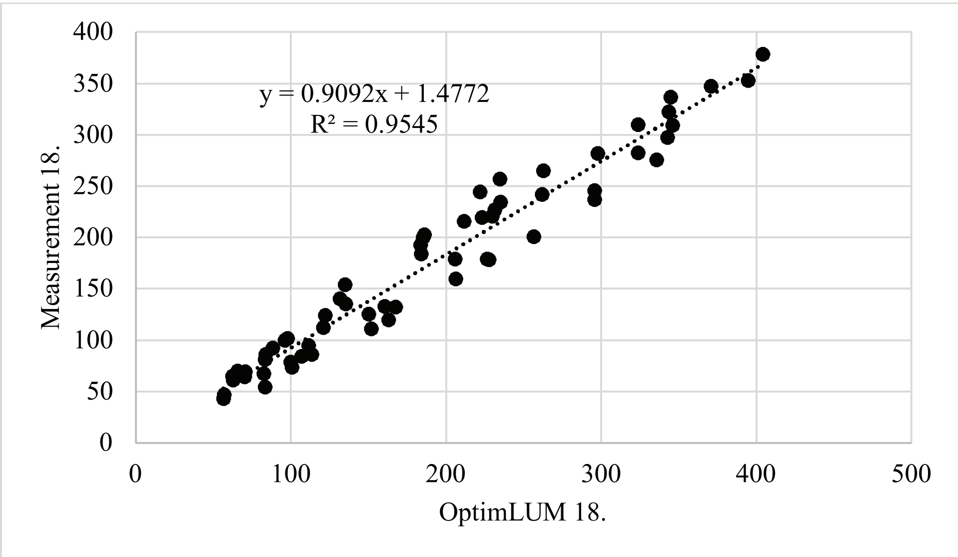


Figure A.24. Scatter diagram of single configuration of Alternative I layout (18) for LED luminaire.

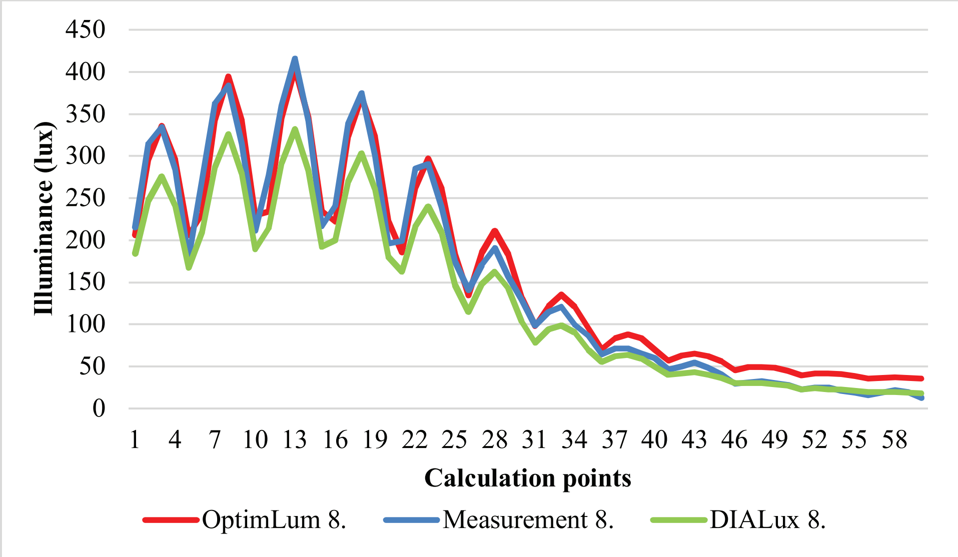


Figure A.25. Distributions of illuminance values in single configuration of Alternative I layout (8) for LED luminaire.

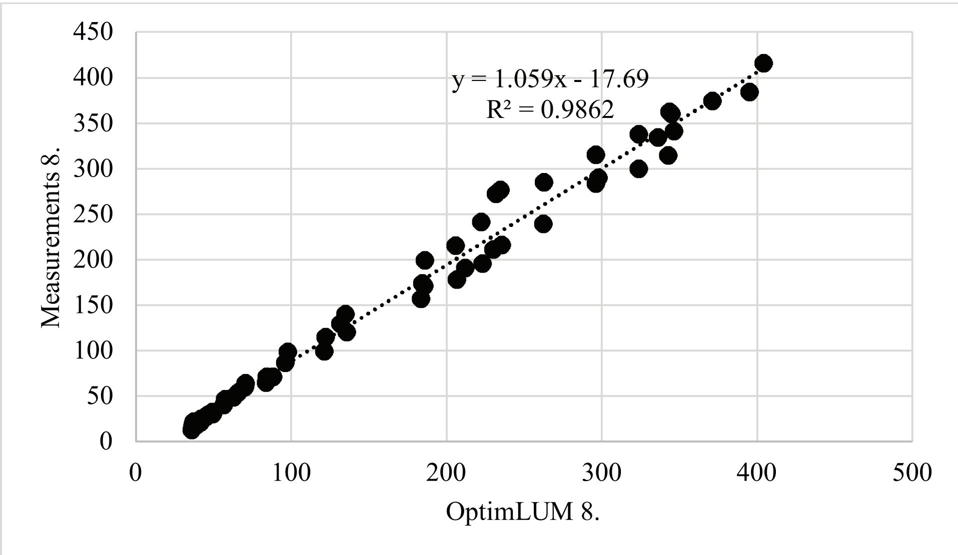


Figure A.26. Scatter diagram of single configuration of Alternative I layout (8) for LED luminaire.

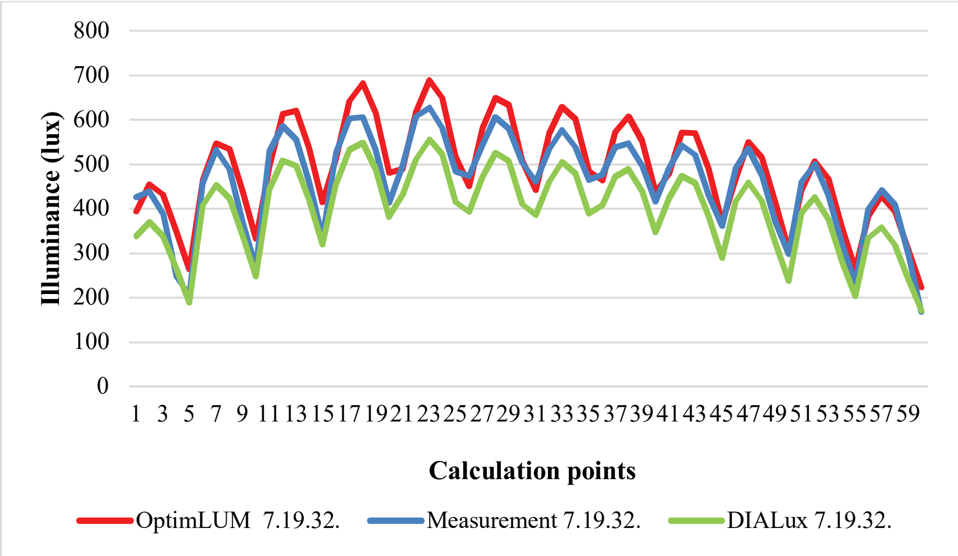


Figure A.27. Distributions of illuminance values Alternative II layout (7.19.32) for LED luminaire.

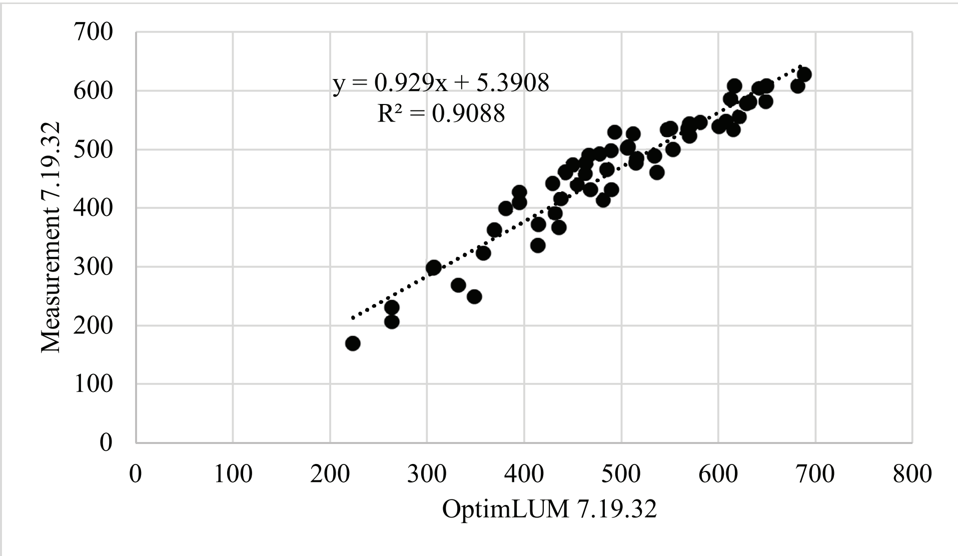


Figure A.28. Scatter diagram of Alternative II layout (7.19.32) for LED luminaire.

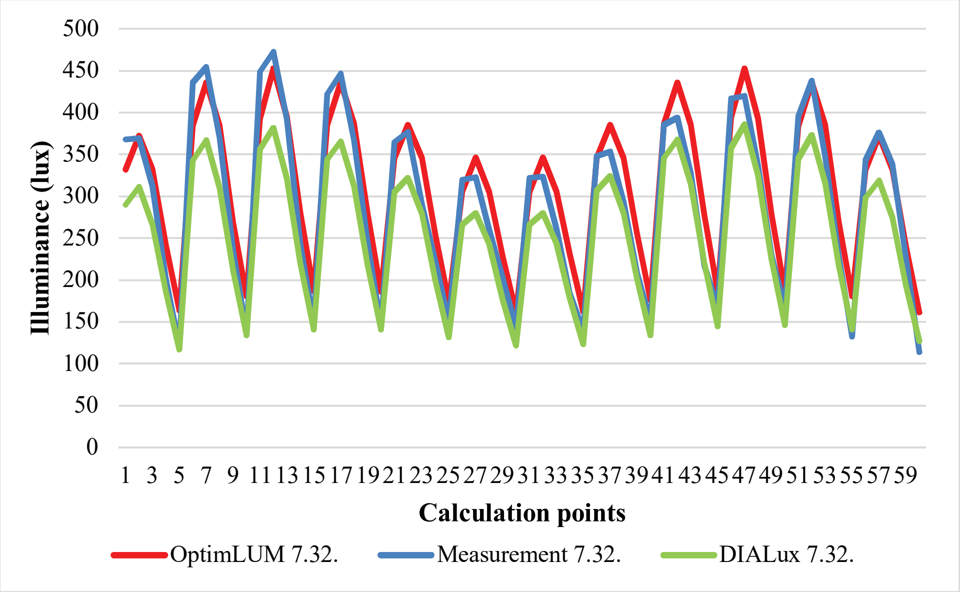


Figure A.29. Distributions of illuminance values in double configuration of Alternative II layout (7.32) for LED luminaire.

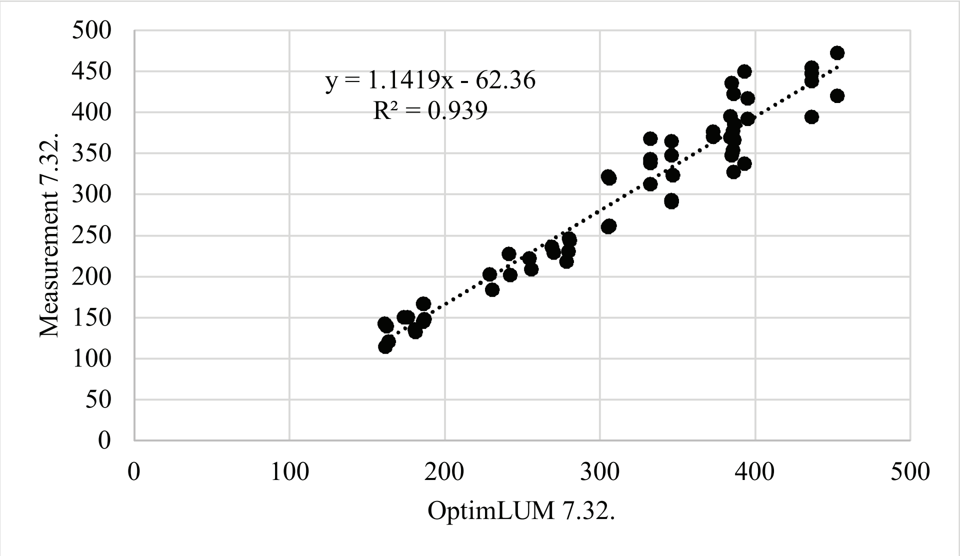


Figure A.30. Scatter diagram of double configuration of Alternative II layout (7.32) for LED luminaire.

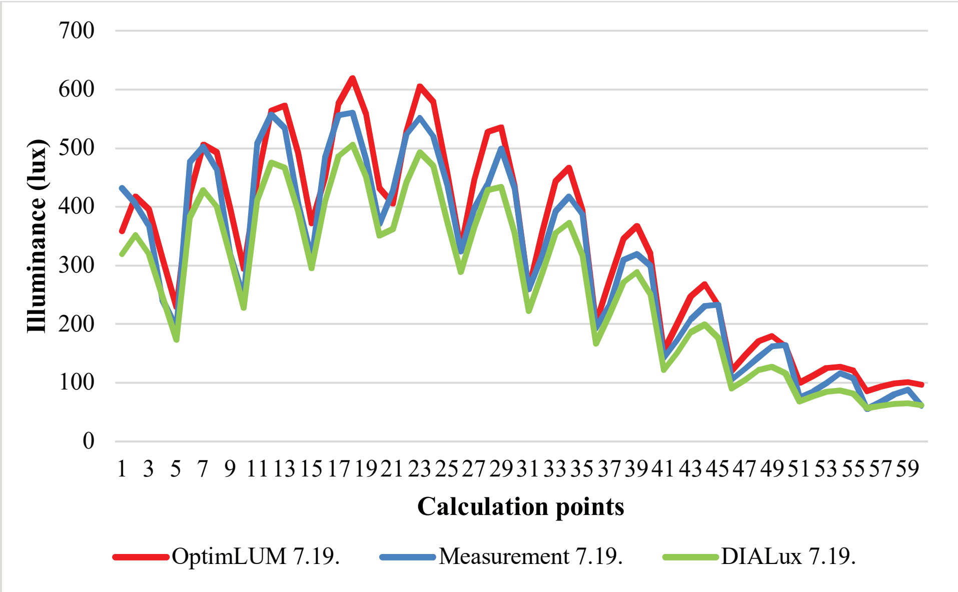


Figure A.31. Distributions of illuminance values in double configuration of Alternative II layout (7.19) for LED luminaire.

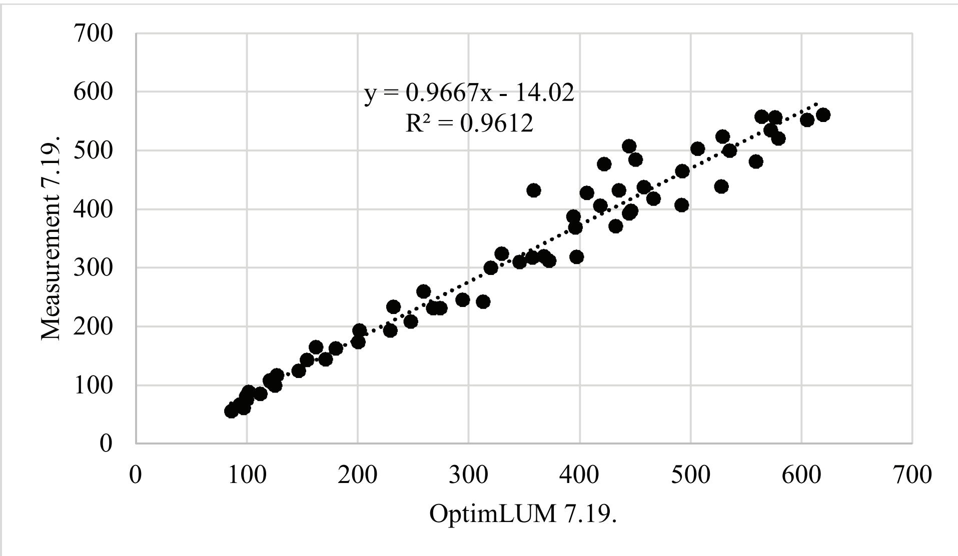


Figure A.32. Scatter diagram of double configuration of Alternative II layout (7.19) for LED luminaire.

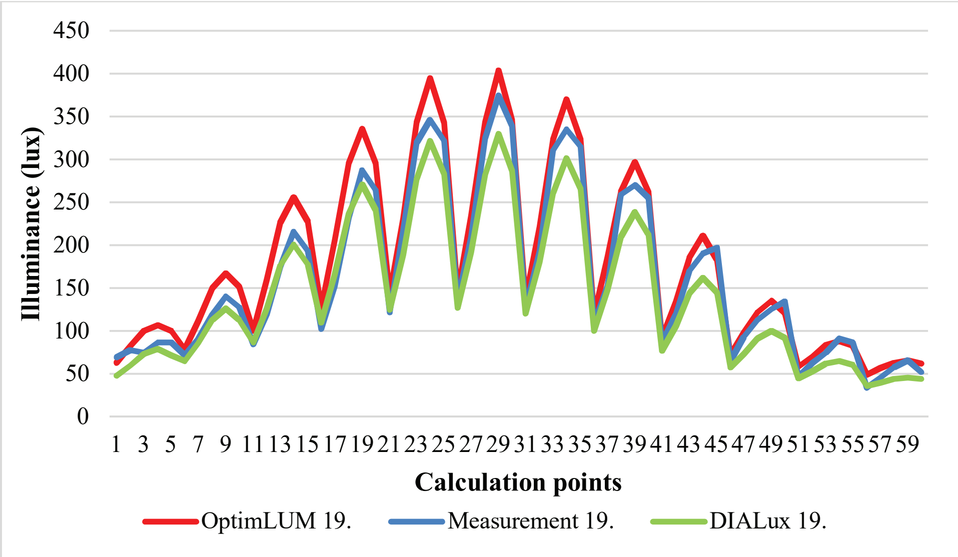


Figure A.33. Distributions of illuminance values in single configuration of Alternative II layout (19) for LED luminaire.

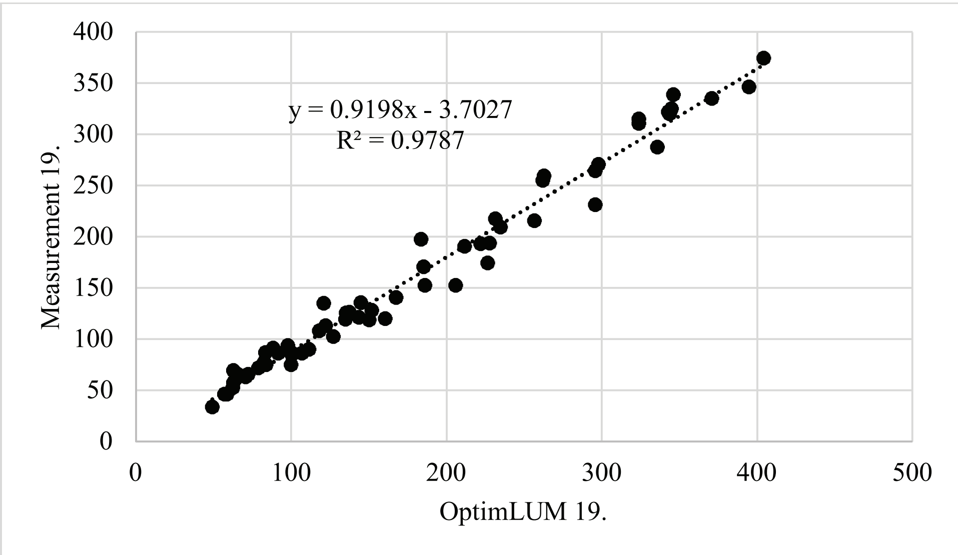


Figure A.34. Scatter diagram of single configuration of Alternative II layout (19) for LED luminaire.

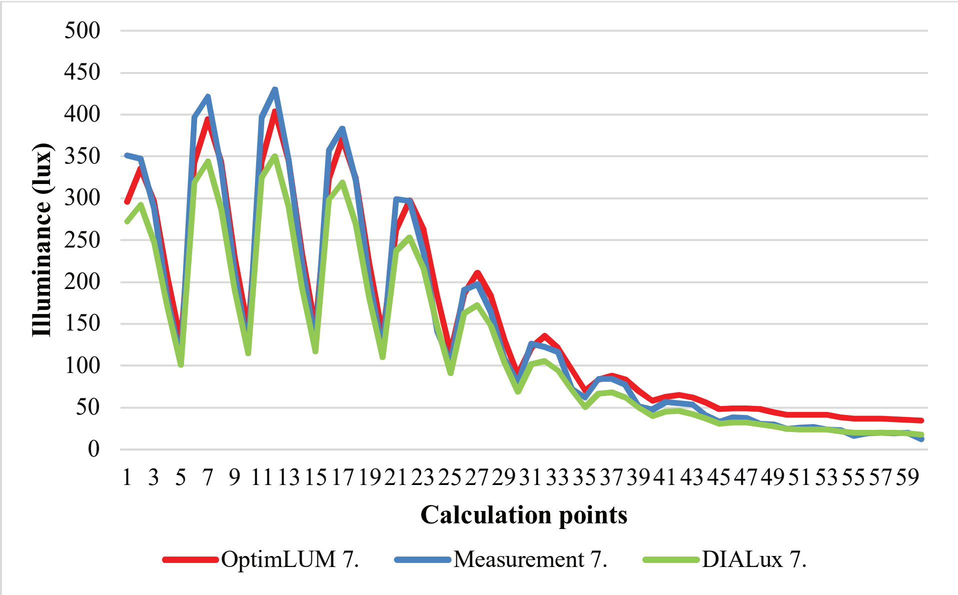


Figure A.35. Distributions of illuminance values in single configuration of Alternative II layout (7) for LED luminaire.

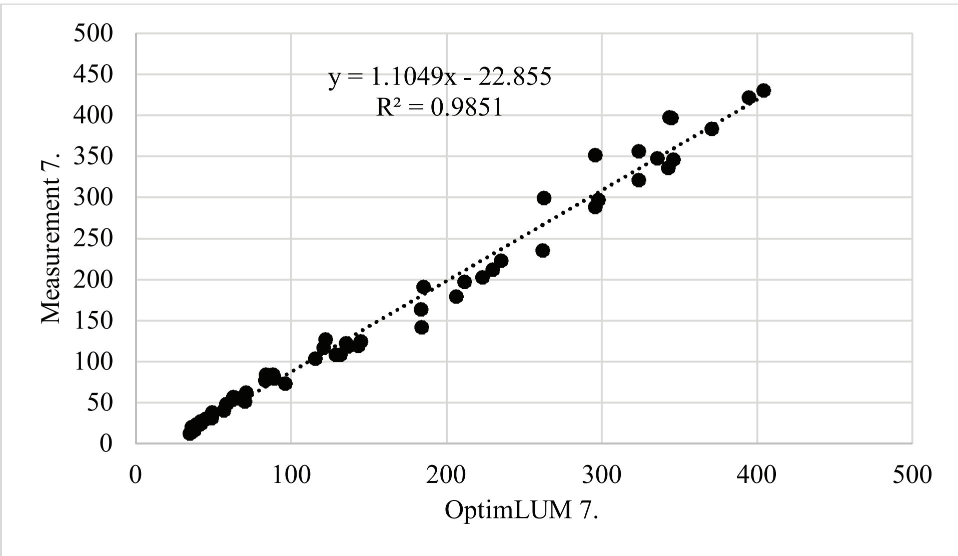


Figure A.36. Scatter diagram of single configuration of Alternative II layout (7) for LED luminaire.

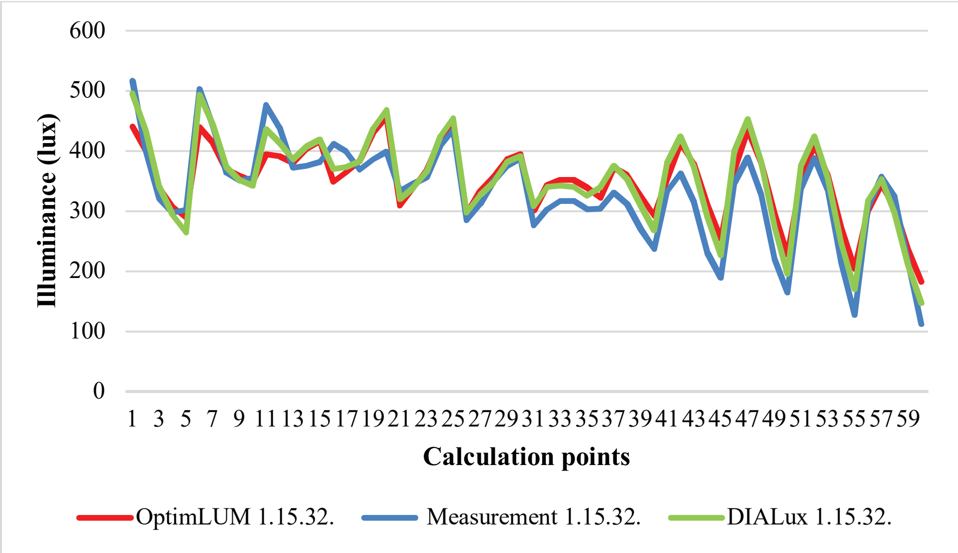


Figure A.37. Distributions of illuminance values in OptimLUM layout (1.15.32) for fluorescent luminaire.

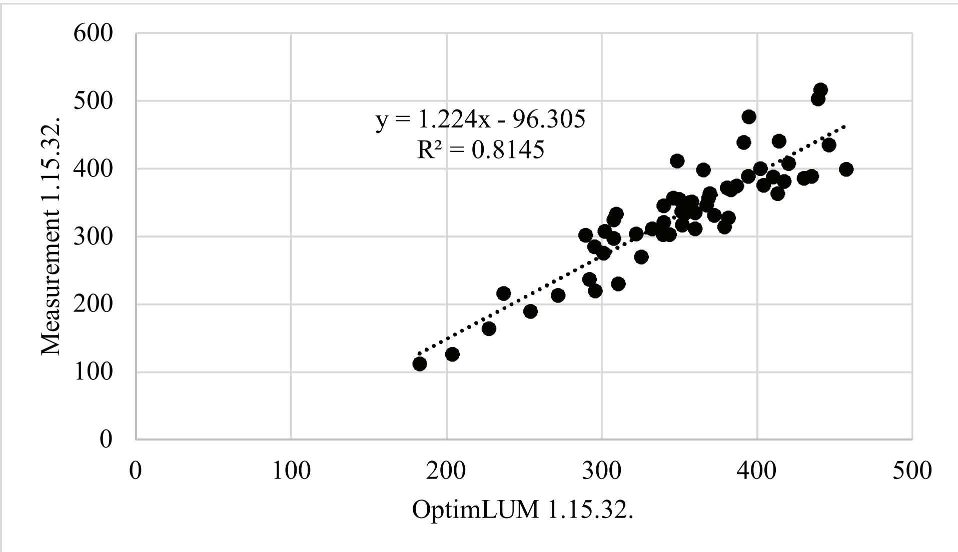


Figure A.38. Scatter diagram of OptimLUM layout (1.15.32) for fluorescent luminaire.

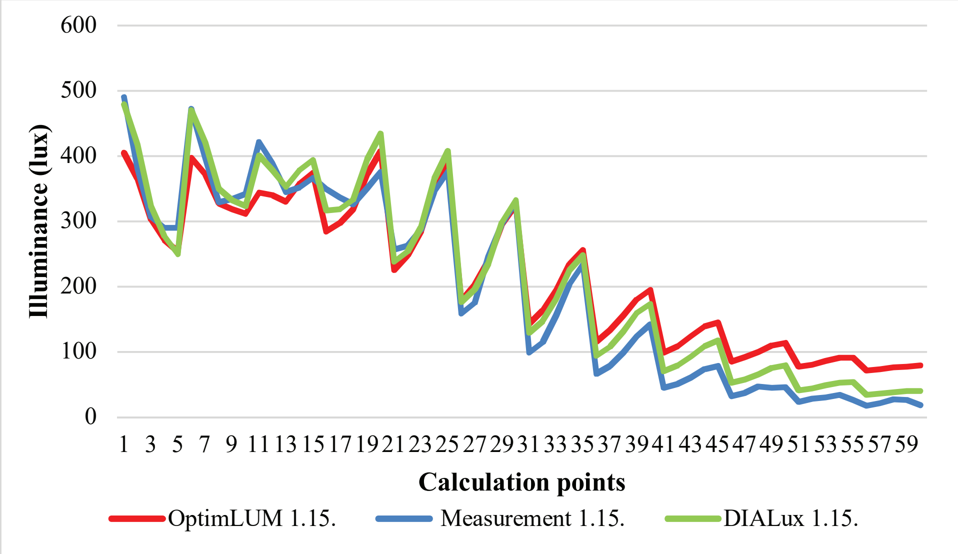


Figure A.39. Distributions of illuminance values in double configuration OptimLUM layout (1.15) for fluorescent luminaire.

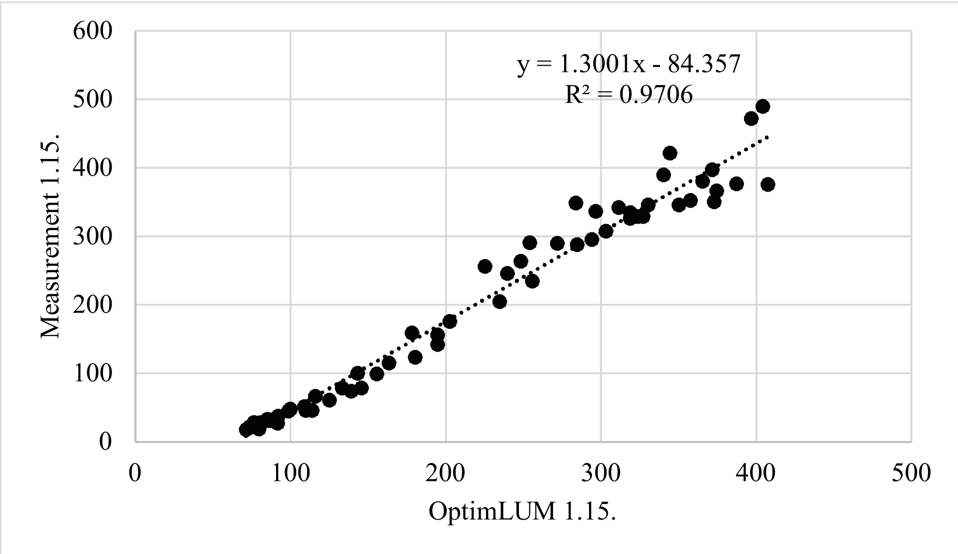


Figure A.40. Scatter diagram of double configuration of OptimLUM layout (1.15) for fluorescent luminaire.

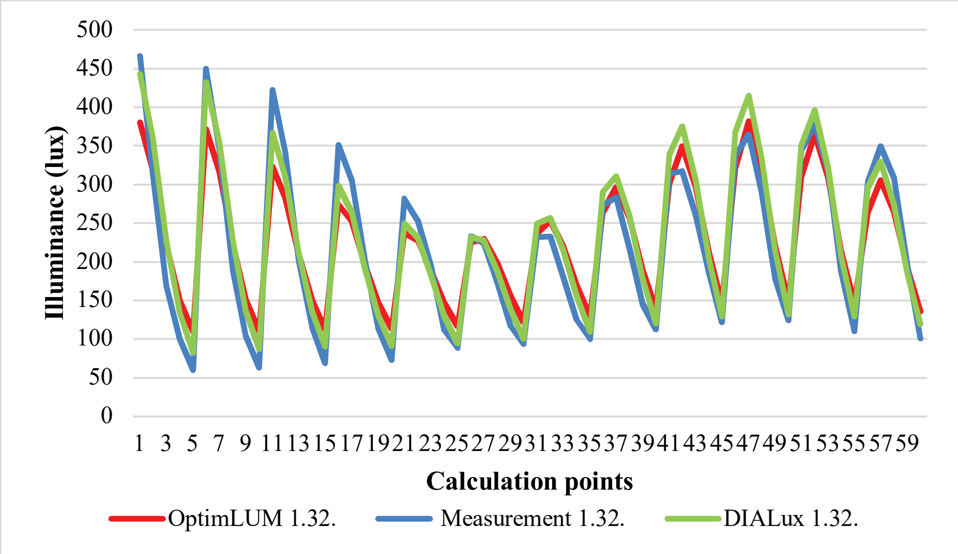


Figure A.41. Distributions of illuminance values in double configuration OptimLUM layout (1.32) for fluorescent luminaire.

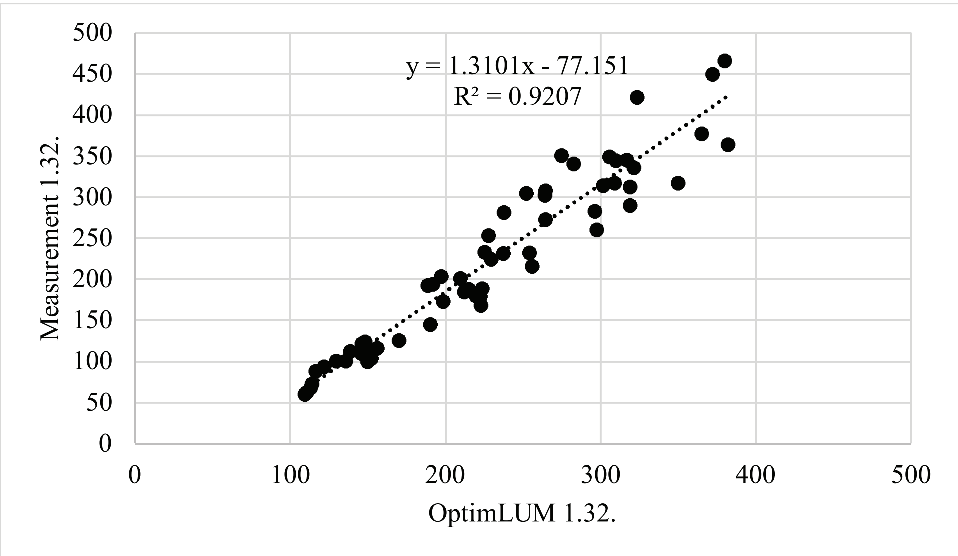


Figure A.42. Scatter diagram of double configuration of OptimLUM layout (1.32) for fluorescent luminaire.

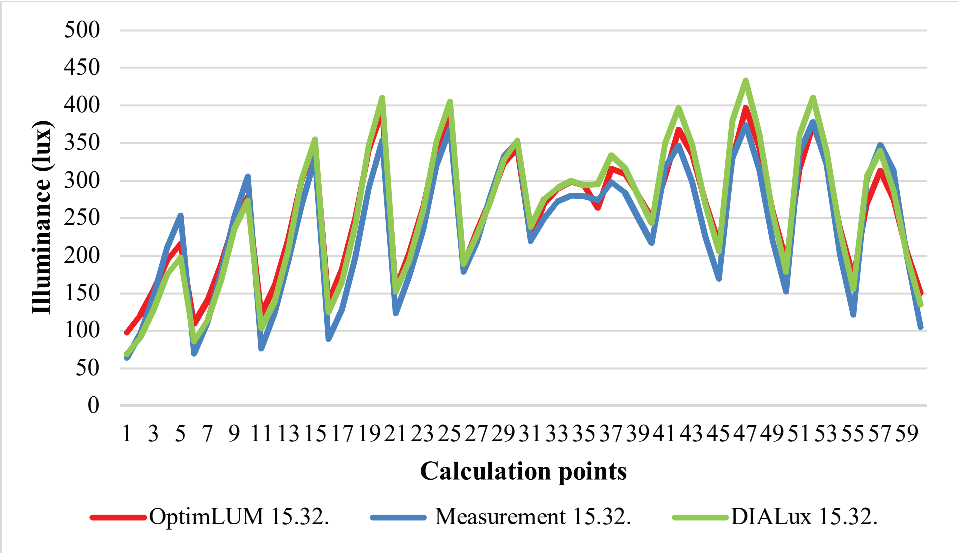


Figure A.43. Distributions of illuminance values in double configuration OptimLUM layout (15.32) for fluorescent luminaire.

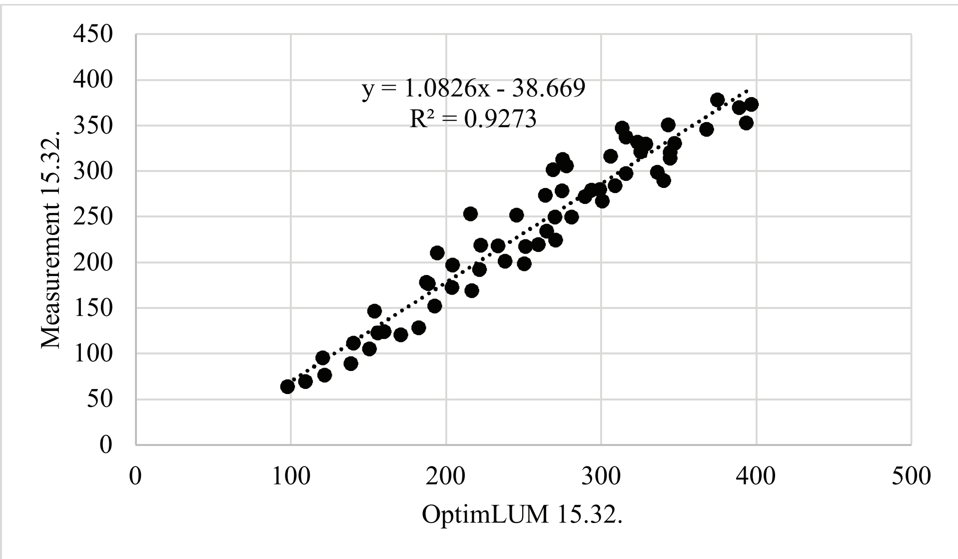


Figure A.44. Scatter diagram of double configuration of OptimLUM layout (15.32) for fluorescent luminaire.

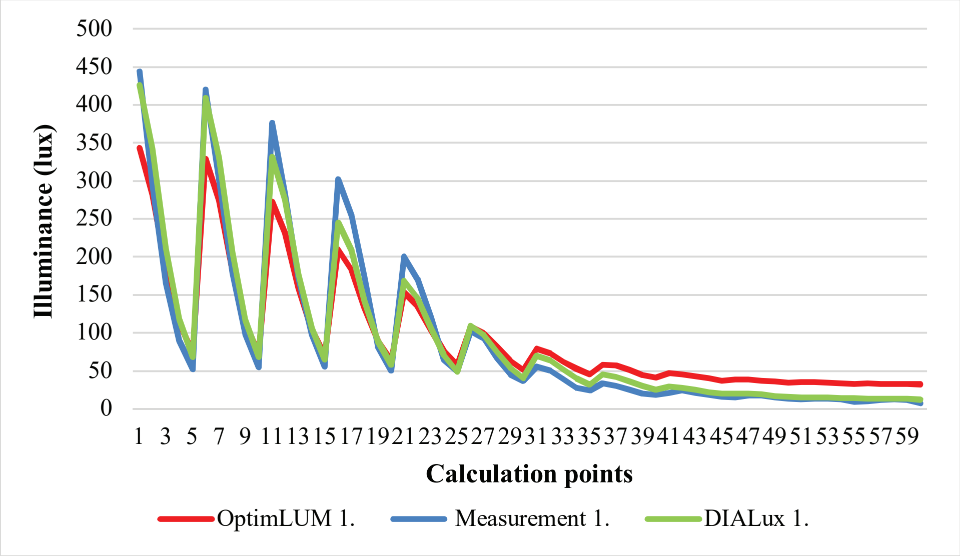


Figure A.45. Distributions of illuminance values in single configuration OptimLUM layout (1) for fluorescent luminaire.

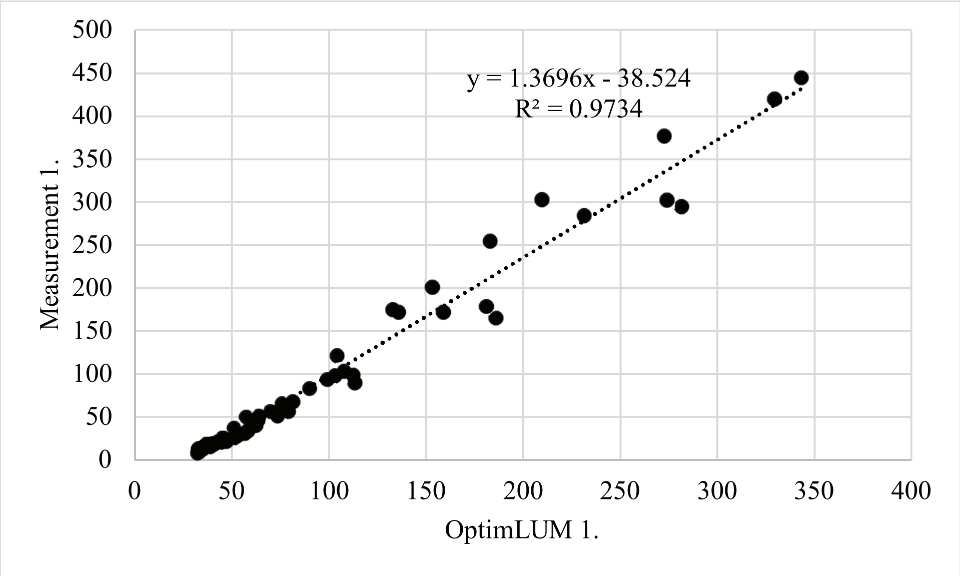


Figure A.46. Scatter diagram of single configuration of OptimLUM layout (1) for fluorescent luminaire.

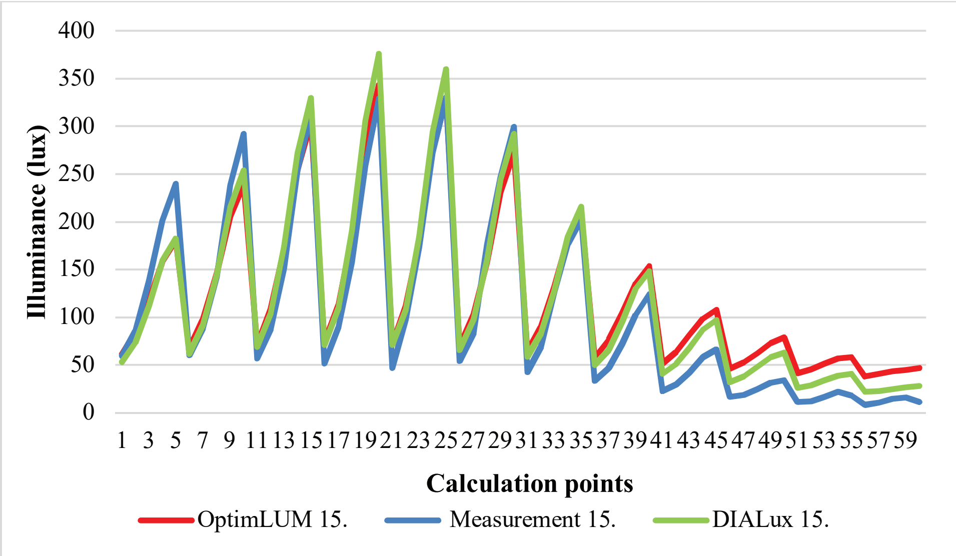


Figure A.47. Distributions of illuminance values in single configuration OptimLUM layout (15) for fluorescent luminaire.

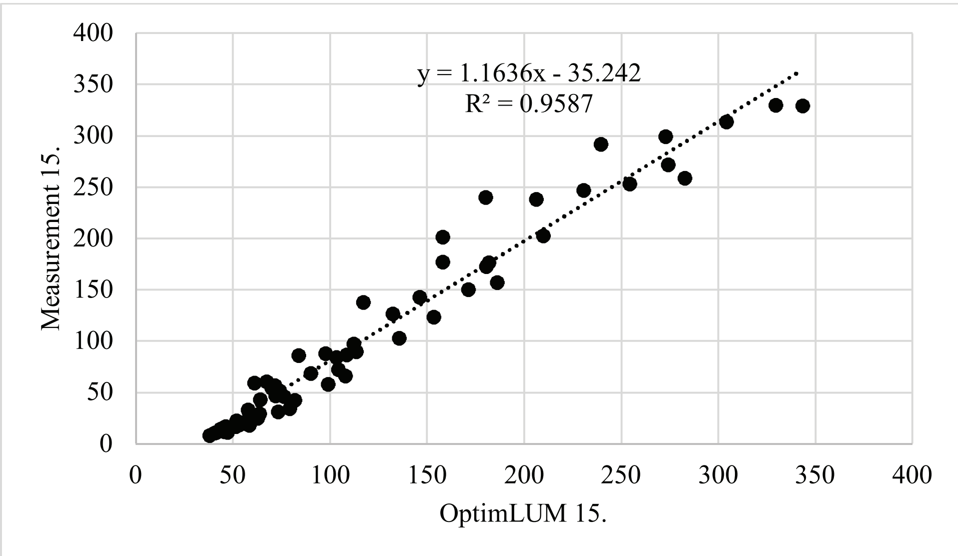


Figure A.48. Scatter diagram of single configuration of OptimLUM layout (15) for fluorescent luminaire.

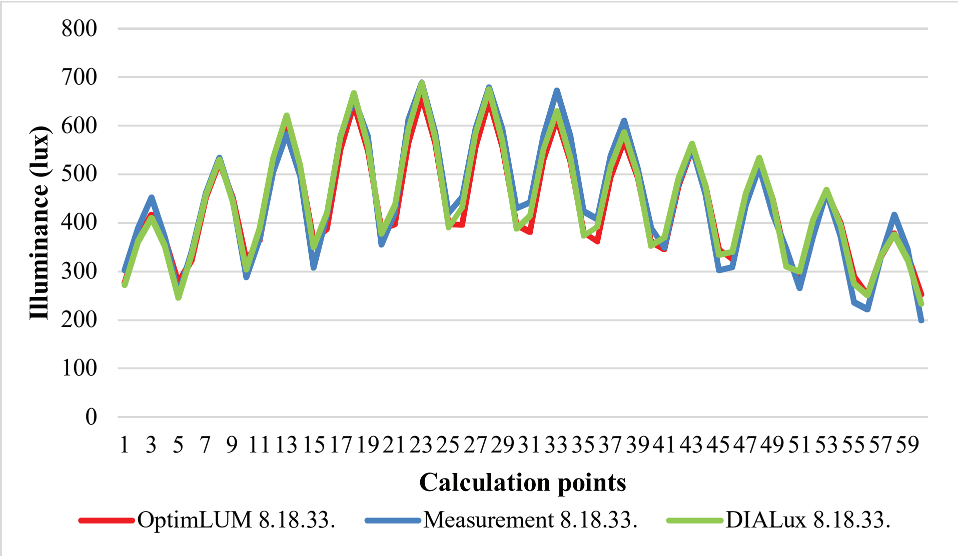


Figure A.49. Distributions of illuminance values in Alternative layout (8.18.33) for fluorescent luminaire.

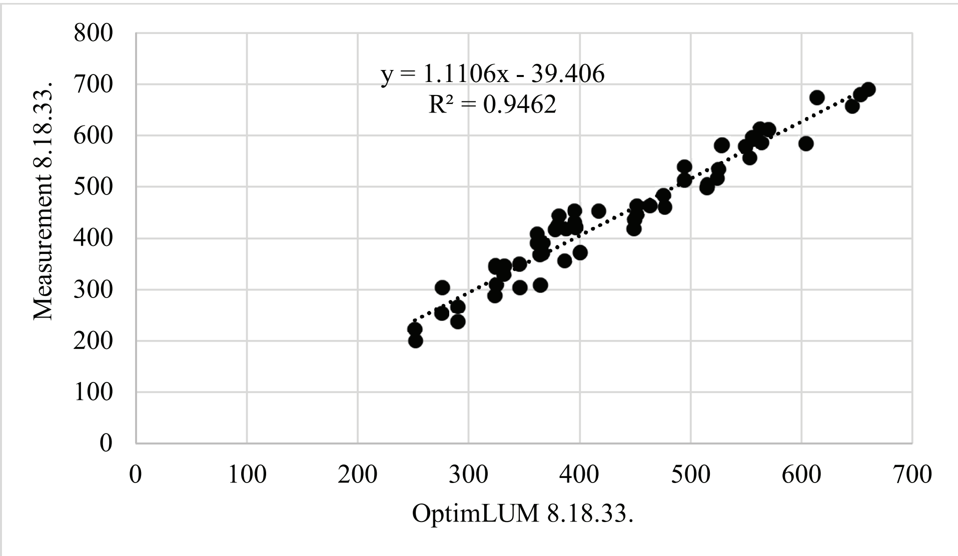


Figure A.50. Scatter diagram of Alternative I OptimLUM layout (8.18.33) for fluorescent luminaire.

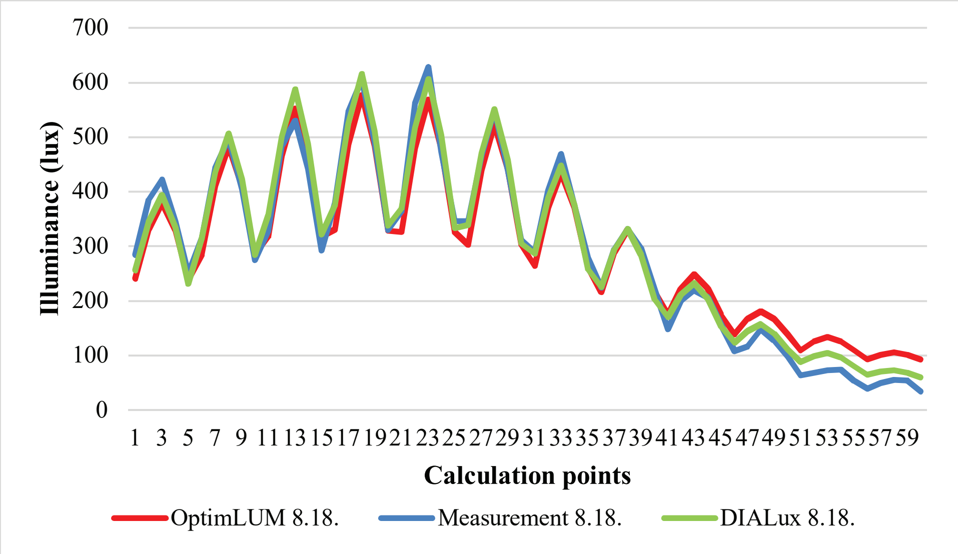


Figure A.51. Distributions of illuminance values in double configuration of Alternative I layout (8.18) for fluorescent luminaire.

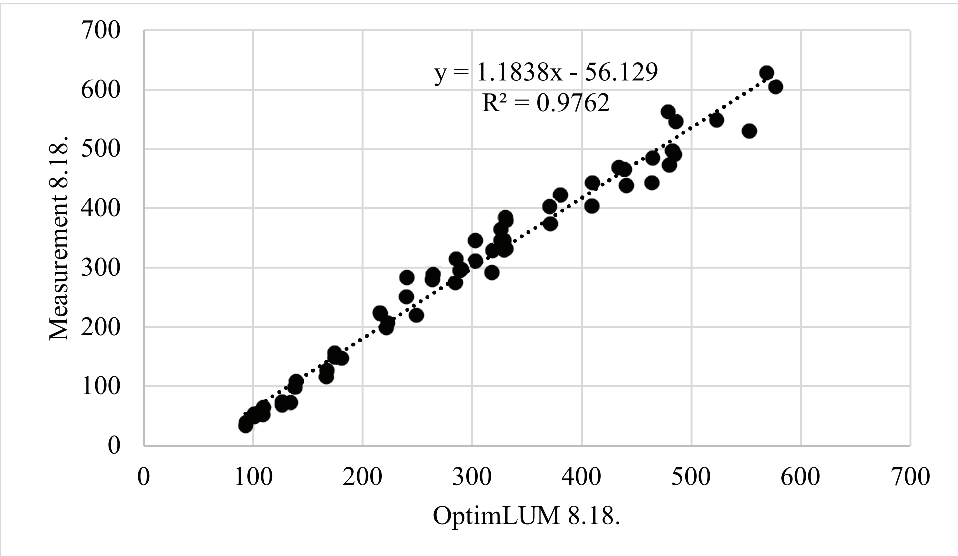


Figure A.52. Scatter diagram of double configuration of Alternative I layout (8.18) for fluorescent luminaire.

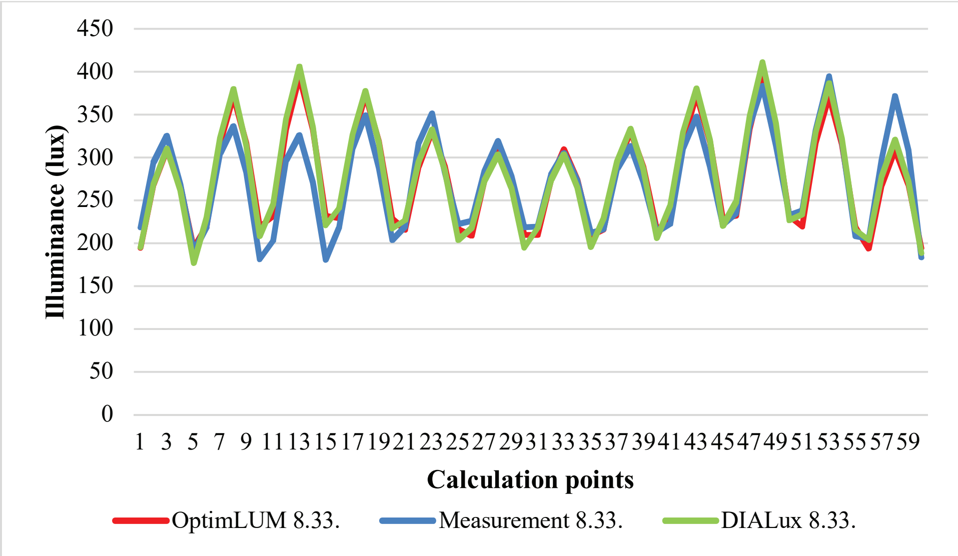


Figure A.53. Distributions of illuminance values in double configuration of Alternative I layout (8.33) for fluorescent luminaire.

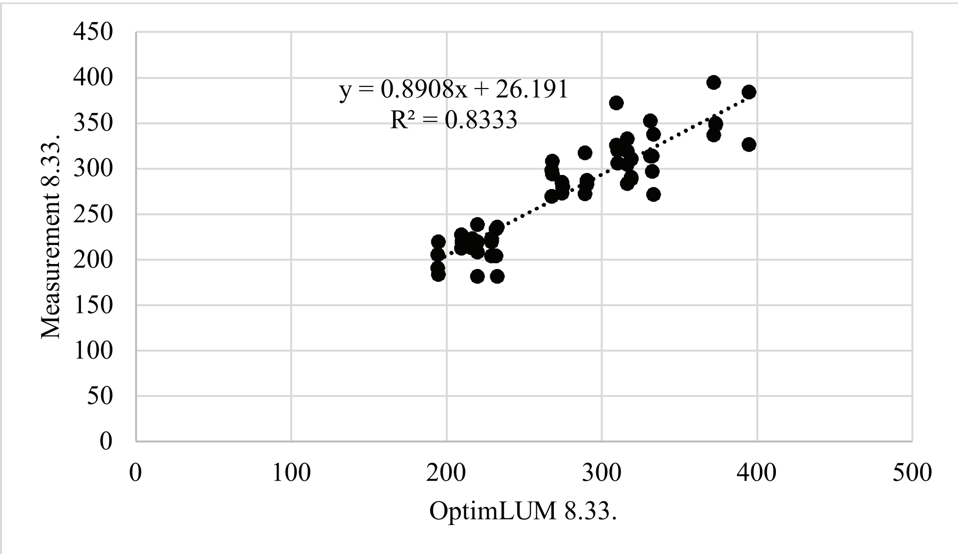


Figure A.54. Scatter diagram of double configuration of Alternative I layout (8.33) for fluorescent luminaire.

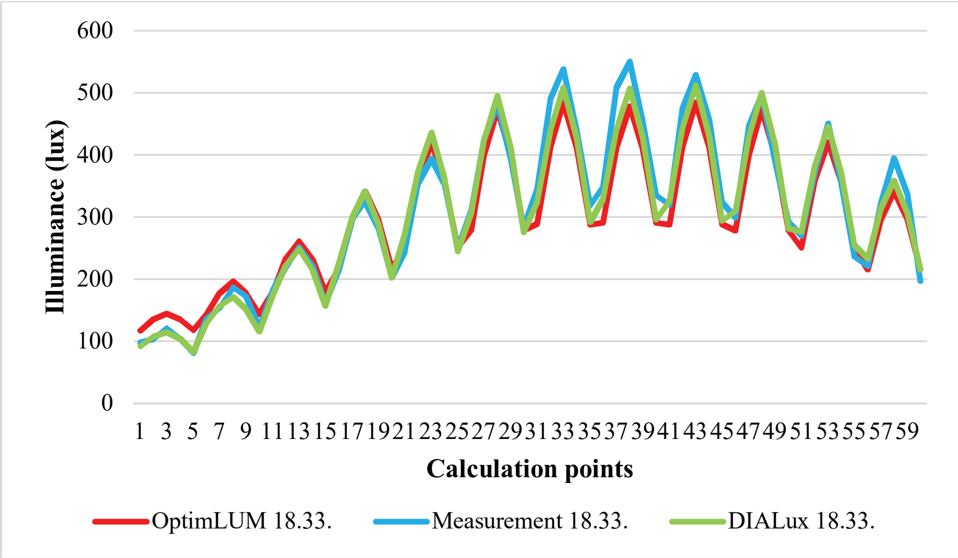


Figure A.55. Distributions of illuminance values in double configuration of Alternative I layout (18.33) for fluorescent luminaire.

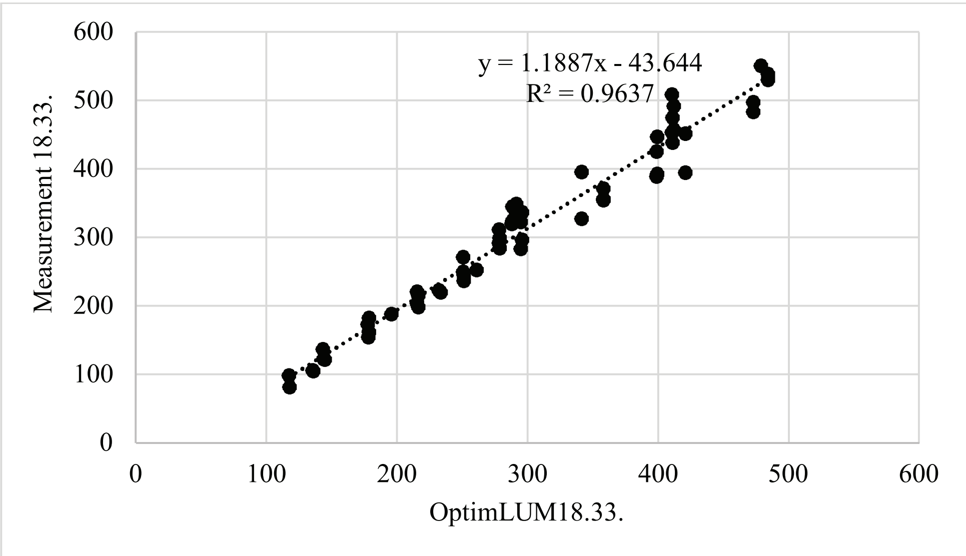


Figure A.56. Scatter diagram of double configuration of Alternative I layout (18.33) for fluorescent luminaire.

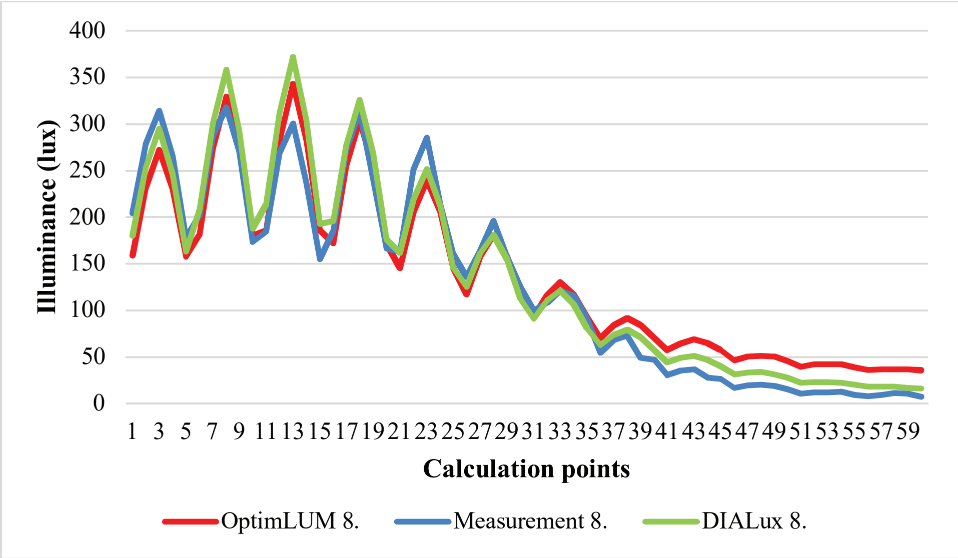


Figure A.57. Distributions of illuminance values in single configuration of Alternative I layout (8) for fluorescent luminaire.

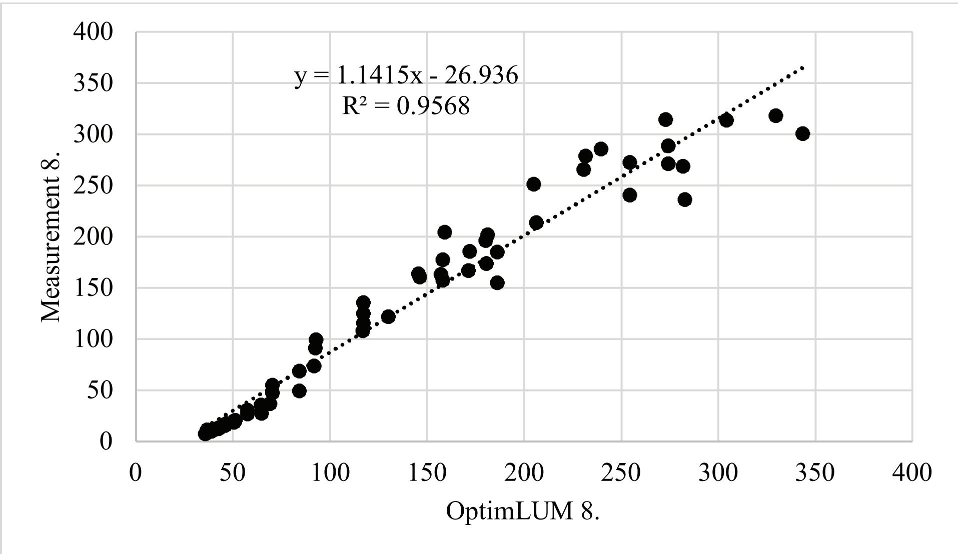


Figure A.58. Scatter diagram of single configuration of Alternative I layout (8) for fluorescent luminaire.

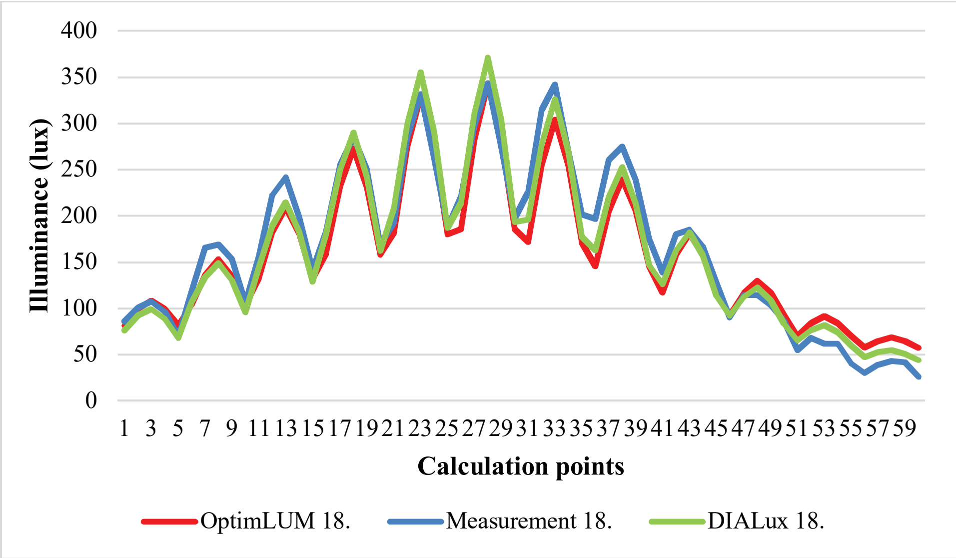


Figure A.59. Distributions of illuminance values in single configuration of Alternative I layout (18) for fluorescent luminaire.

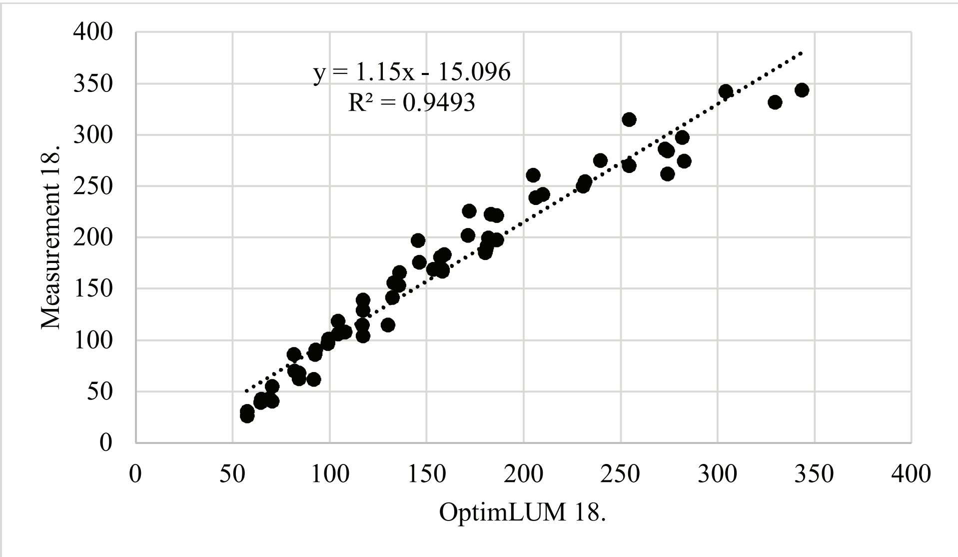


Figure A.60. Scatter diagram of single configuration of Alternative I layout (18) for fluorescent luminaire.

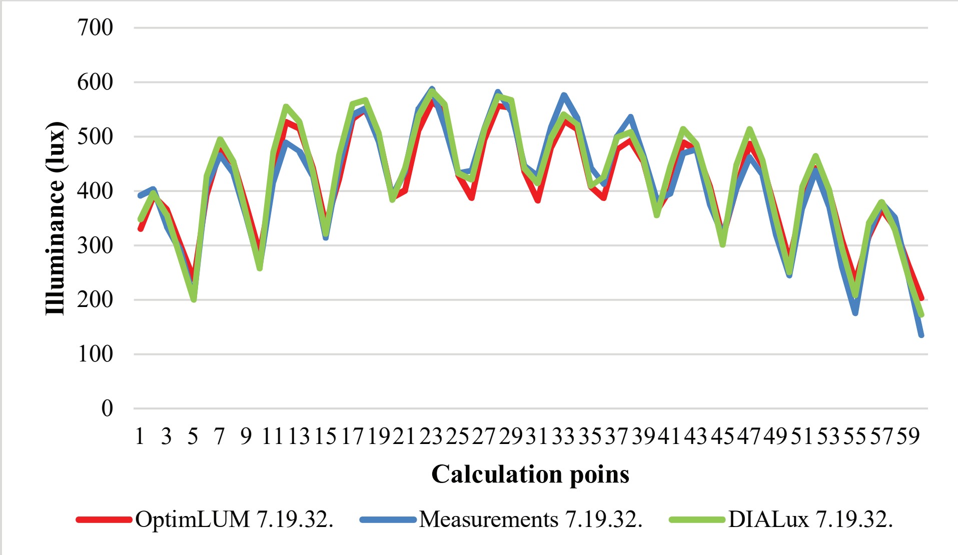


Figure A.61. Distributions of illuminance values in Alternative II layout (7.19.32) for fluorescent luminaire.

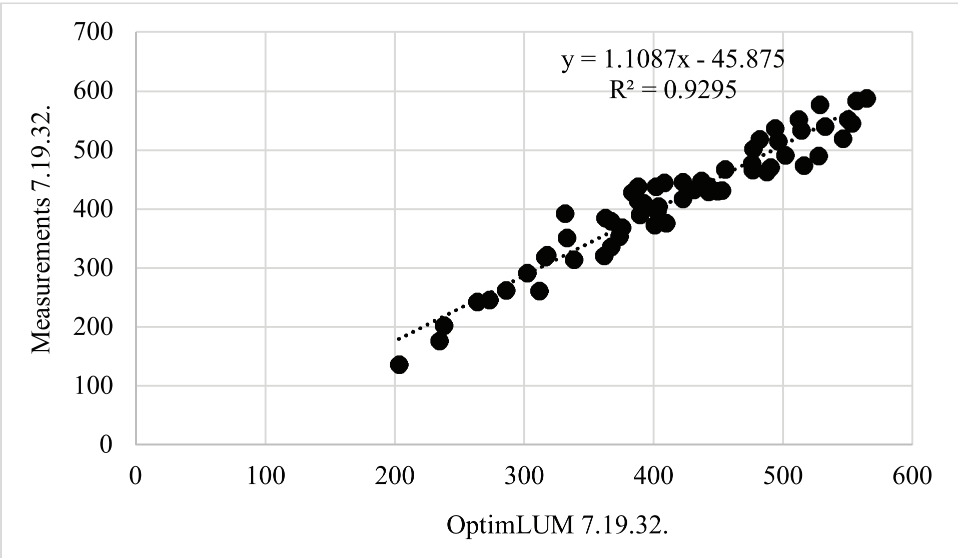


Figure A.62. Scatter diagram of Alternative II layout (7.19.32) for fluorescent luminaire.

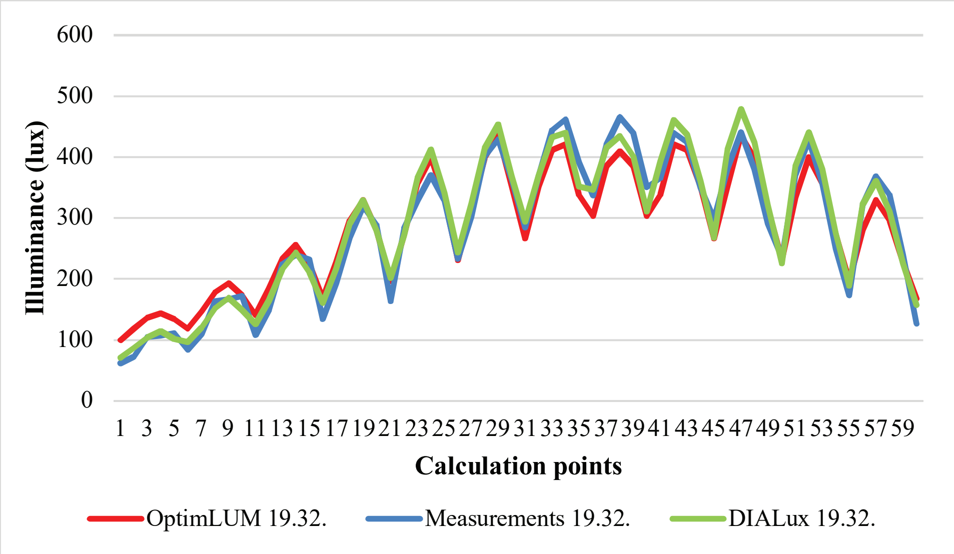


Figure A.63. Distributions of illuminance values in double configuration of Alternative II layout (19.32) for fluorescent luminaire.

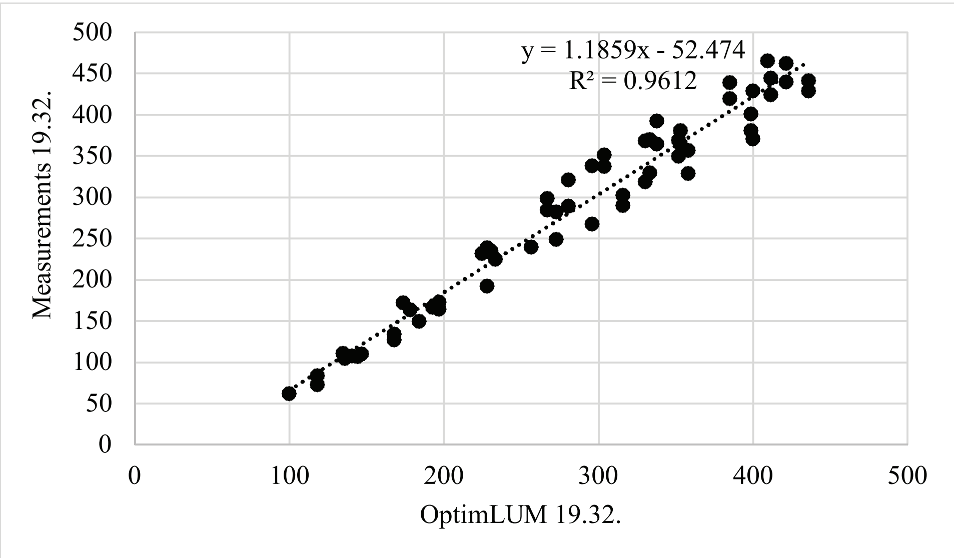


Figure A.64. Scatter diagram of double configuration of Alternative II layout (19.32) for fluorescent luminaire.

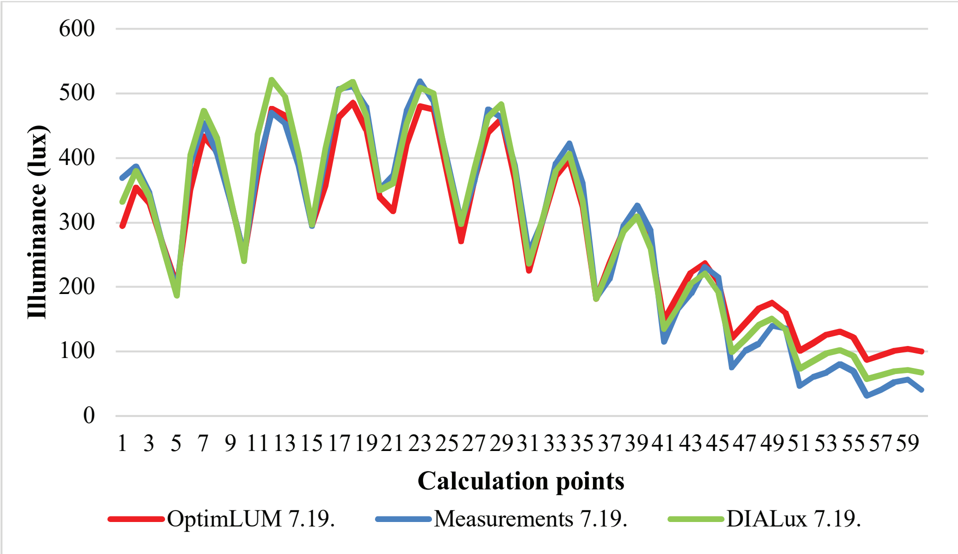


Figure A.65. Distributions of illuminance values in double configuration of Alternative II layout (7.19) for fluorescent luminaire.

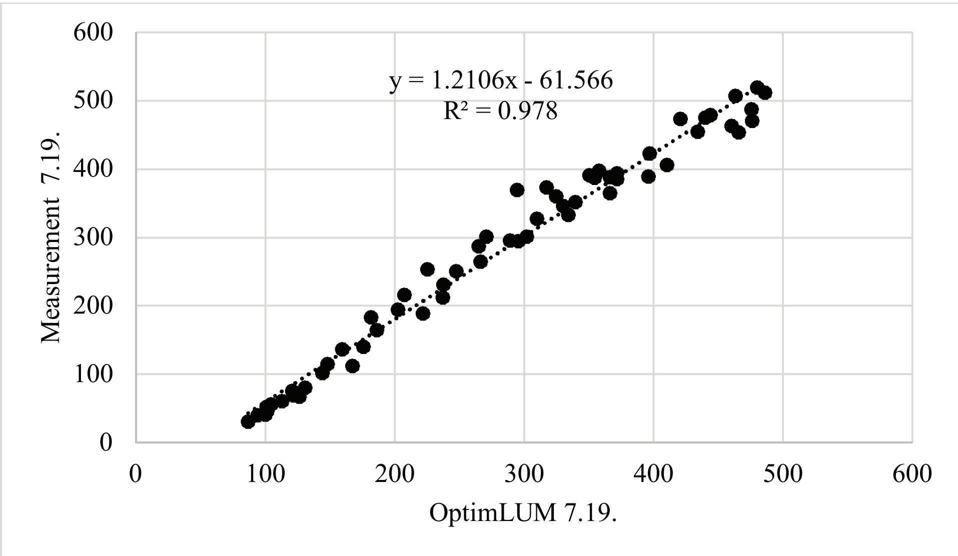


Figure A.66. Scatter diagram of double configuration of Alternative II layout (7.19) for fluorescent luminaire.

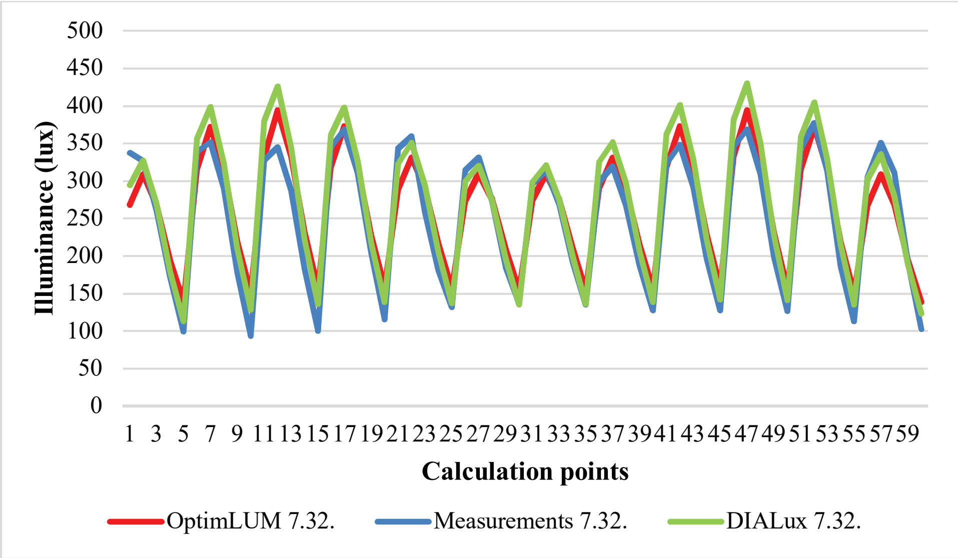


Figure A.67. Distributions of illuminance values in double configuration of Alternative II layout (7.32) for fluorescent luminaire.

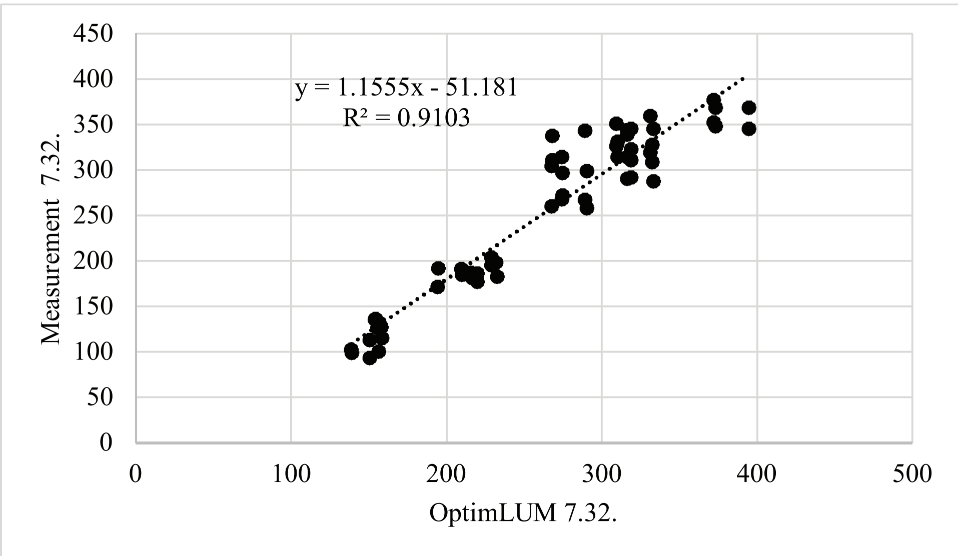


Figure A.68. Scatter diagram of double configuration of Alternative II layout (7.32) for fluorescent luminaire.

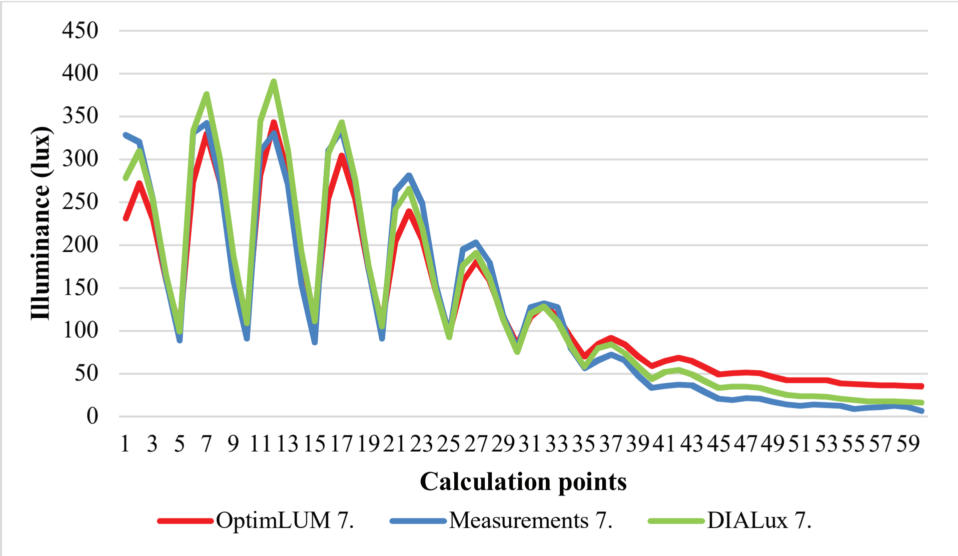


Figure A.69. Distributions of illuminance values in single configuration of Alternative II layout (7) for fluorescent luminaire.

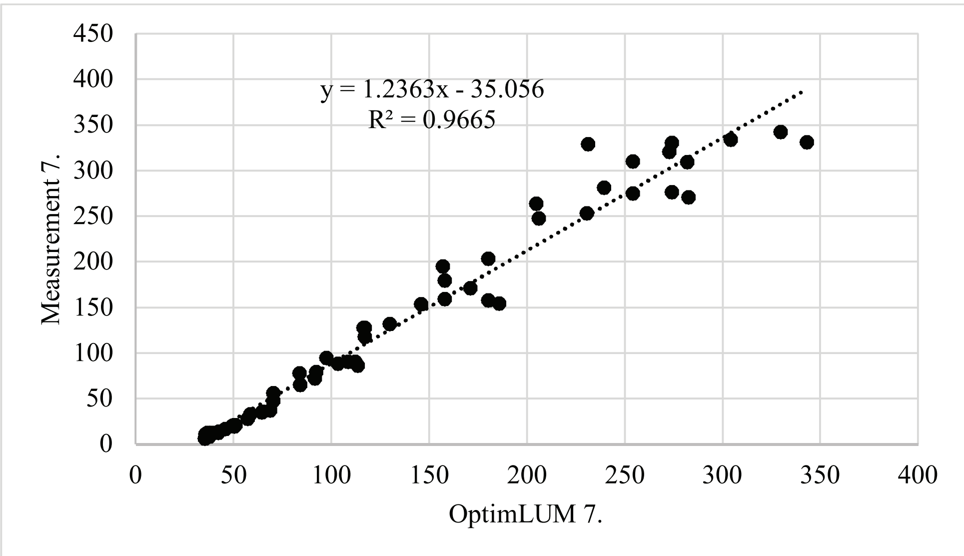


Figure A.70. Scatter diagram of single configuration of Alternative II layout (7) for fluorescent luminaire.

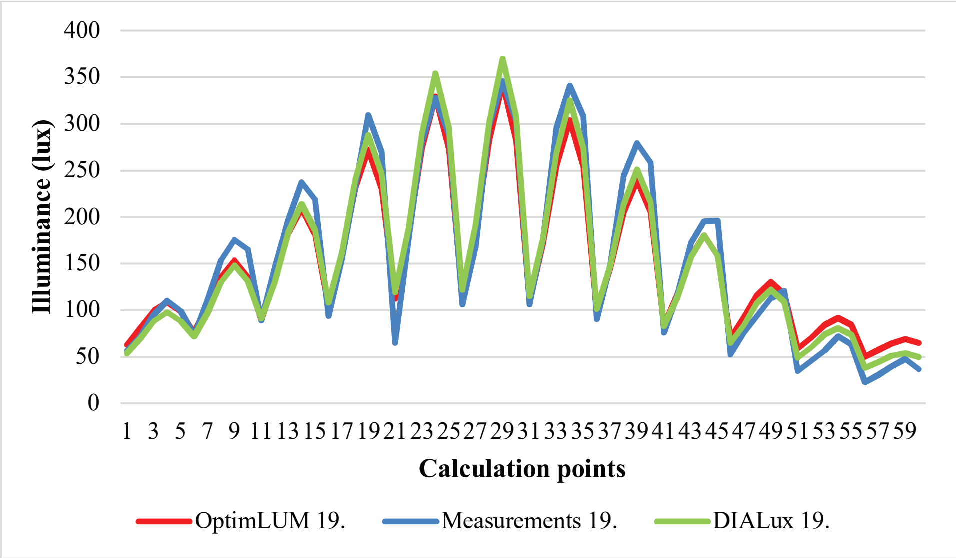


Figure A.71. Distributions of illuminance values in single configuration of Alternative II layout (19) for fluorescent luminaire.

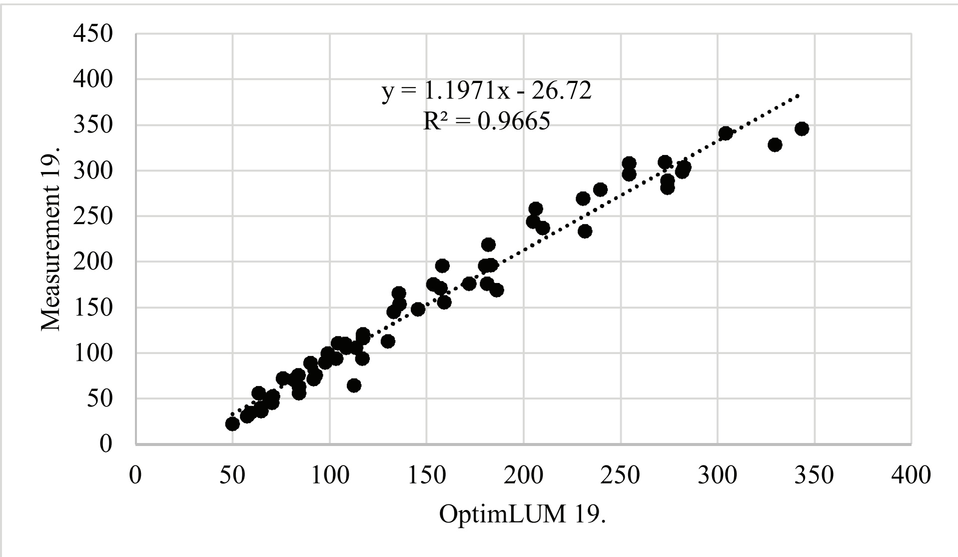
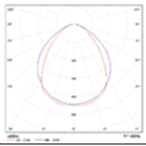


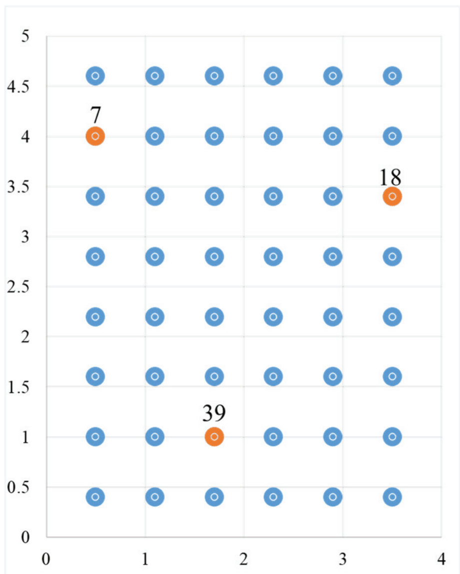
Figure A.72. Scatter diagram of single configuration of Alternative II layout (19) for fluorescent luminaire.

APPENDIX B

OptimLUM LAYOUTS AND OUTPUTS

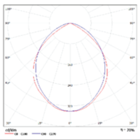
Table B.1. Layout and output of OptimLUM for small room with Luminaire 1.

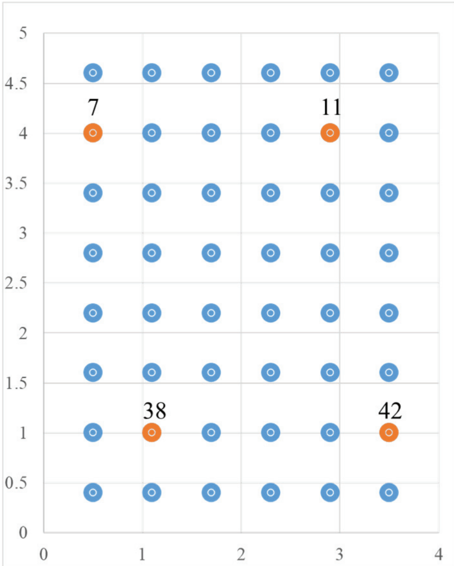
1	PHILIPS CoreLine Surface-mounted (SM120V LED37S/840 PSU W60L60)			3700 lumen	93 lm/W	42 W



E_{avg}	446.69 lux
U	0.11
E_{wall1}/E_{work}	0.61
E_{wall2}/E_{work}	0.72
E_{wall3}/E_{work}	0.62
E_{wall4}/E_{work}	0.73
$L_{wall1;avg}$	51.69 cd/m^2
$L_{wall2;avg}$	61.74 cd/m^2
$L_{wall3;avg}$	53.01 cd/m^2
$L_{wall4;avg}$	62.62 cd/m^2
Valid Trials	384
Total Trials	23737
Total Opt.Time	0:25:10

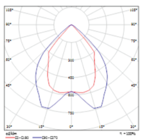
Table B.2. Layout and output of OptimLUM for small room with Luminaire 2.

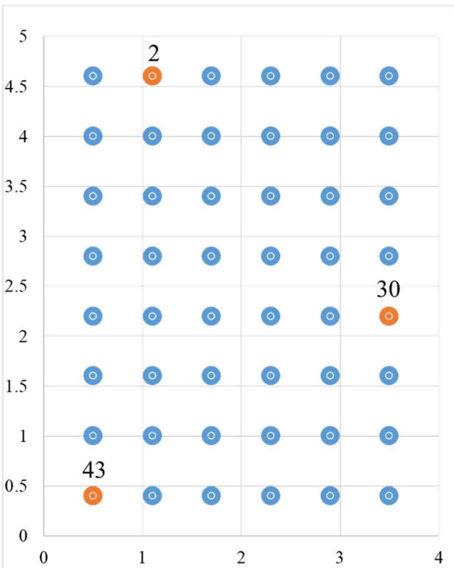
2	PHILIPS Centura 2 (TCS160 4xTL-D18W HF C3)			3780 lumen	209 lm/W	69.5 W



E_{avg}	476.82 lux
U	0.05
E_{wall1}/E_{work}	0.69
E_{wall2}/E_{work}	0.76
E_{wall3}/E_{work}	0.69
E_{wall4}/E_{work}	0.76
$L_{wall1;avg}$	63.14 cd/m^2
$L_{wall2;avg}$	68.99 cd/m^2
$L_{wall3;avg}$	63.14 cd/m^2
$L_{wall4;avg}$	68.99 cd/m^2
Valid Trials	856
Total Trials	21769
Total Opt.Time	0:22:58

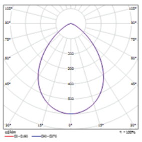
Table B.3. Layout and output of OptimLUM for small room with Luminaire 3.

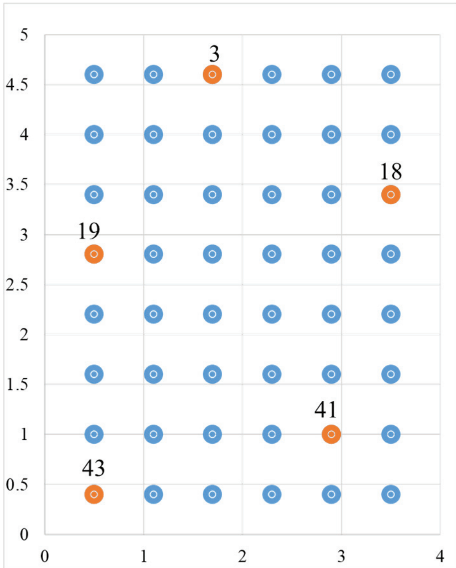
3	OSRAM SITECO 51MT1LV0JHGEB B02 Taris®2			3930 lumen	131 lm/W	30 W



E_{avg}	476.90 lux
U	0.21
E_{wall1}/E_{work}	0.66
E_{wall2}/E_{work}	0.59
E_{wall3}/E_{work}	0.73
E_{wall4}/E_{work}	0.57
$L_{wall1;avg}$	59.92 cd/m^2
$L_{wall2;avg}$	53.40 cd/m^2
$L_{wall3;avg}$	66.93 cd/m^2
$L_{wall4;avg}$	51.98 cd/m^2
Valid Trials	109
Total Trials	20723
Total Opt.Time	0:16:50

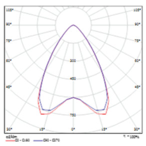
Table B.4. Layout and output of OptimLUM for small room with Luminaire 4.

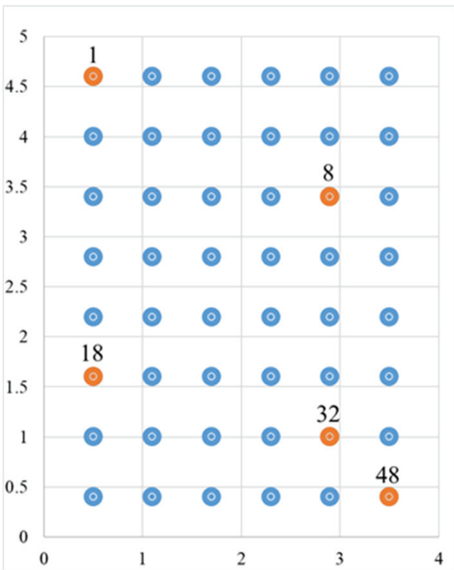
4	OSRAM SITECO 0DX11A7833S LEDVALUX® XL (Lunis)			1970 lumen	104 lm/W	19 W



E_{avg}	409.63 lux
U	0.05
E_{wall1}/E_{work}	0.71
E_{wall2}/E_{work}	0.65
E_{wall3}/E_{work}	0.72
E_{wall4}/E_{work}	0.74
$L_{wall1;avg}$	55.16 cd/m^2
$L_{wall2;avg}$	51.22 cd/m^2
$L_{wall3;avg}$	55.94 cd/m^2
$L_{wall4;avg}$	58.25 cd/m^2
Valid Trials	456
Total Trials	28556
Total Opt.Time	0:29:03

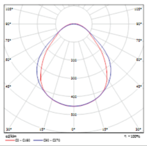
Table B.5. Layout and output of OptimLUM for small room with Luminaire 5.

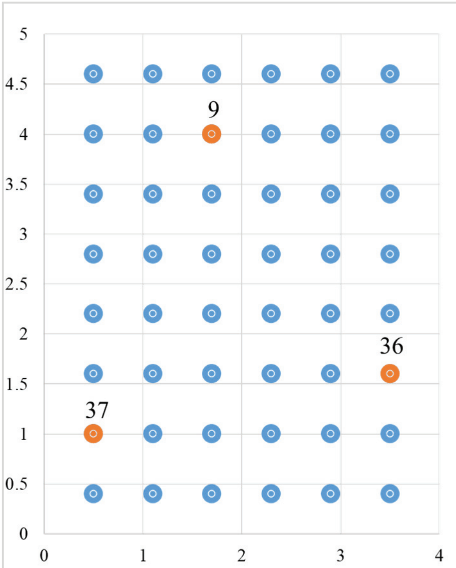
5	OSRAM SITECO 5MZ212D03WA Scriptus®			2195 lumen	127 lm/W	17.3 W



E_{avg}	414.431 ux
U	0.09
E_{wall1}/E_{work}	0.64
E_{wall2}/E_{work}	0.73
E_{wall3}/E_{work}	0.76
E_{wall4}/E_{work}	0.68
$L_{wall1;avg}$	50.66 cd/m^2
$L_{wall2;avg}$	57.56 cd/m^2
$L_{wall3;avg}$	59.91 cd/m^2
$L_{wall4;avg}$	53.74 cd/m^2
Valid Trials	303
Total Trials	23537
Total Opt.Time	0:29:42

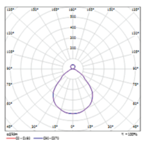
Table B.6. Layout and output of OptimLUM for small room with Luminaire 6.

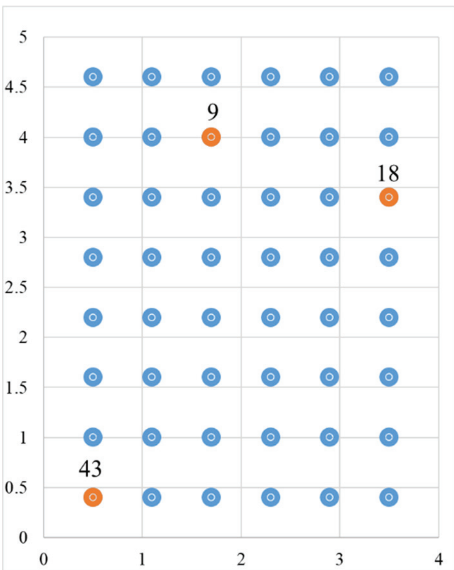
6	Zumtobel 42185186 MLevo AA LED3600-840 Q LDO SR			3450 lumen	115 lm/W	30.4 W



E_{avg}	411.97 lux
U	0.11
E_{wall1}/E_{work}	0.66
E_{wall2}/E_{work}	0.76
E_{wall3}/E_{work}	0.64
E_{wall4}/E_{work}	0.77
$L_{wall1;avg}$	51.84 cd/m^2
$L_{wall2;avg}$	59.81 cd/m^2
$L_{wall3;avg}$	50.38 cd/m^2
$L_{wall4;avg}$	60.75 cd/m^2
Valid Trials	270
Total Trials	23358
Total Opt.Time	0:29:46

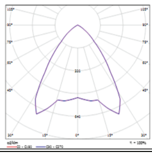
Table B.7. Layout and output of OptimLUM for small room with Luminaire 7.

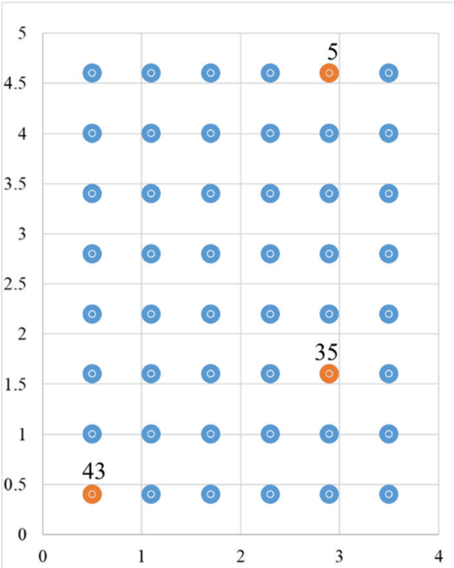
7	Zumtobel 42184475 LFE DI LED4600-840 Q LDO ASH1 SRE (Light Fields)			4530 lumen	121 lm/W	37.5 W



E_{avg}	499.59 lux
U	0.23
E_{wall1}/E_{work}	0.78
E_{wall2}/E_{work}	0.80
E_{wall3}/E_{work}	0.74
E_{wall4}/E_{work}	0.74
$L_{wall1;avg}$	74.33 cd/m^2
$L_{wall2;avg}$	76.09 cd/m^2
$L_{wall3;avg}$	71.00 cd/m^2
$L_{wall4;avg}$	70.30 cd/m^2
Valid Trials	10
Total Trials	20932
Total Opt.Time	0:26:50

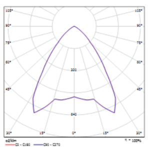
Table B.8. Layout and output of OptimLUM for small room with Luminaire 8.

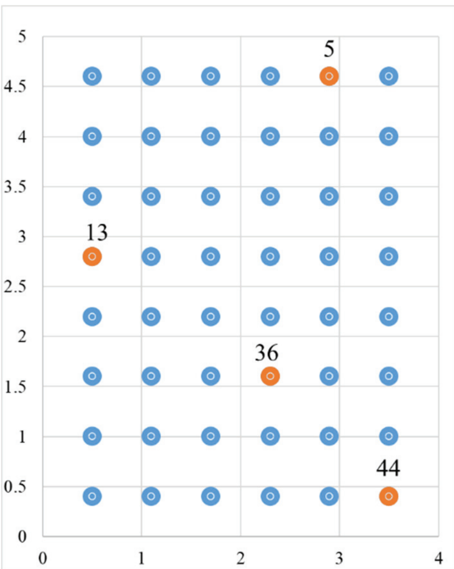
8	Zumtobel 42182361 MIREL-L LAY LED3800-840 M600Q EVG KA			3740 lumen	134 lm/W	28 W



E_{avg}	480.47lux
U	0.25
E_{wall1}/E_{work}	0.76
E_{wall2}/E_{work}	0.57
E_{wall3}/E_{work}	0.78
E_{wall4}/E_{work}	0.55
$L_{wall1;avg}$	69.68 cd/m^2
$L_{wall2;avg}$	51.98 cd/m^2
$L_{wall3;avg}$	71.47 cd/m^2
$L_{wall4;avg}$	50.84 cd/m^2
Valid Trials	468
Total Trials	23182
Total Opt.Time	0:33:41

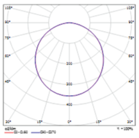
Table B.9. Layout and output of OptimLUM for small room with Luminaire 9.

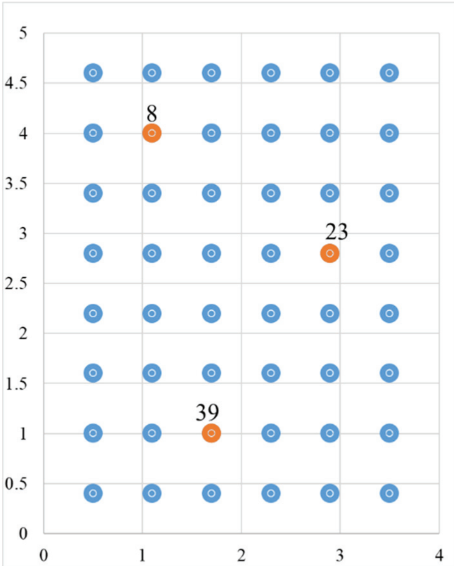
9	Zumtobel 42925916 MIREL-L LAY LED2800-830 M600Q LDO KA			2600 lumen	130 lm/W	20 W



E_{avg}	442.84 lux
U	0.06
E_{wall1}/E_{work}	0.71
E_{wall2}/E_{work}	0.65
E_{wall3}/E_{work}	0.71
E_{wall4}/E_{work}	0.65
$L_{wall1;avg}$	60.32 cd/m^2
$L_{wall2;avg}$	54.70 cd/m^2
$L_{wall3;avg}$	60.32 cd/m^2
$L_{wall4;avg}$	54.70 cd/m^2
Valid Trials	85
Total Trials	29490
Total Opt.Time	0:28:04

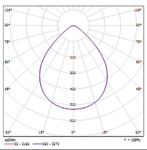
Table B.10. Layout and output of OptimLUM for small room with Luminaire 10.

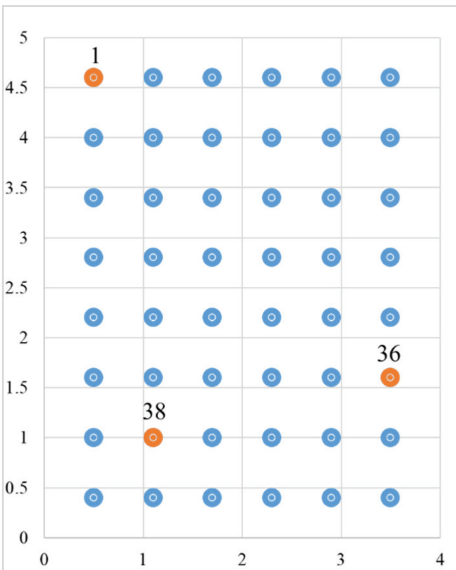
10	Zumtobel 42182369 MIREL-O NIV LED3800-840 M600Q EVG KA			3710 lumen	139 lm/W	26.7 W



E_{avg}	445.39 lux
U	0.13
E_{wall1}/E_{work}	0.73
E_{wall2}/E_{work}	0.70
E_{wall3}/E_{work}	0.74
E_{wall4}/E_{work}	0.72
$L_{wall1;avg}$	61.84 cd/m^2
$L_{wall2;avg}$	59.61 cd/m^2
$L_{wall3;avg}$	63.10 cd/m^2
$L_{wall4;avg}$	61.28 cd/m^2
Valid Trials	1268
Total Trials	20421
Total Opt.Time	0:28:11

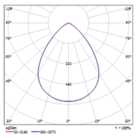
Table B.11. Layout and output of OptimLUM for small room with Luminaire 11.

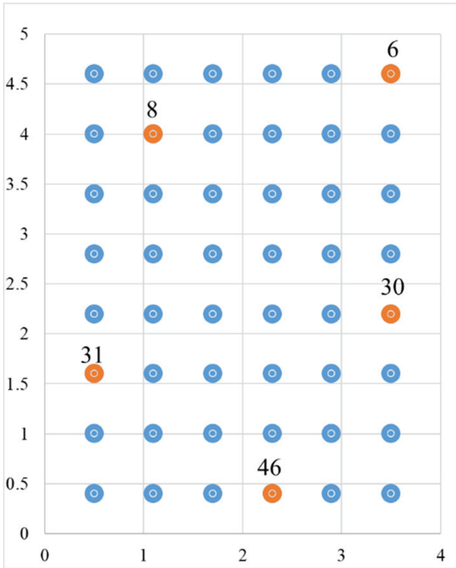
11	PHILIPS RC461B G2 PSD W60L60 1xLED34S/840 (smartbalance)			3400 lumen	142 lm/W	25 W



E_{avg}	409.56 lux
U	0.20
E_{wall1}/E_{work}	0.64
E_{wall2}/E_{work}	0.70
E_{wall3}/E_{work}	0.72
E_{wall4}/E_{work}	0.74
$L_{wall1;avg}$	50.20 cd/m^2
$L_{wall2;avg}$	54.64 cd/m^2
$L_{wall3;avg}$	56.10 cd/m^2
$L_{wall4;avg}$	57.86 cd/m^2
Valid Trials	42
Total Trials	22124
Total Opt.Time	0:29:27

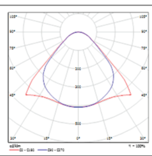
Table B.12. Layout and output of OptimLUM for small room with Luminaire 12.

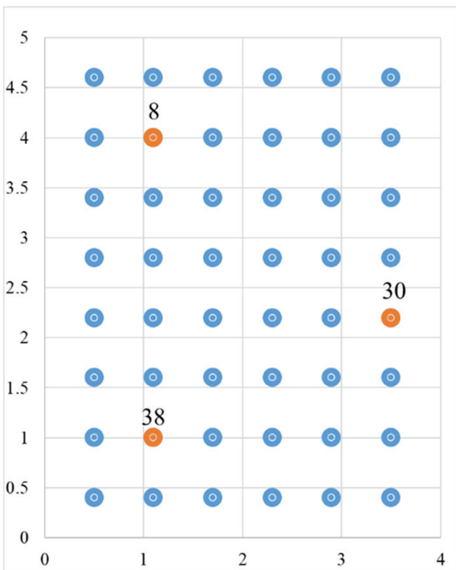
12	PHILIPS DN570B PSED-E 1xLED20S/830 C PG (LuxSpace)			2100 lumen	111 lm/W	19 W



E_{avg}	452.46 lux
U	0.05
E_{wall1}/E_{work}	0.68
E_{wall2}/E_{work}	0.71
E_{wall3}/E_{work}	0.67
E_{wall4}/E_{work}	0.62
$L_{wall1;avg}$	58.84 cd/m^2
$L_{wall2;avg}$	61.01 cd/m^2
$L_{wall3;avg}$	58.05 cd/m^2
$L_{wall4;avg}$	53.31 cd/m^2
Valid Trials	47
Total Trials	22330
Total Opt.Time	0:32:14

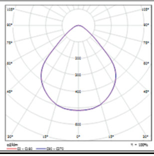
Table B.13. Layout and output of OptimLUM for small room with Luminaire 13.

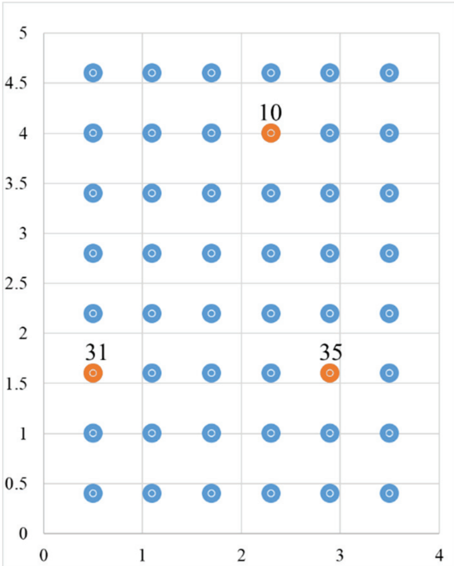
13	PHILIPS SP480P W24L134 1xLED35S/830 ACC-MLO (smartbalance)			3500 lumen	119 lm/W	37 W



E_{avg}	440.93 lux
U	0.11
E_{wall1}/E_{work}	0.66
E_{wall2}/E_{work}	0.79
E_{wall3}/E_{work}	0.63
E_{wall4}/E_{work}	0.72
$L_{wall1;avg}$	55.67 cd/m^2
$L_{wall2;avg}$	66.30 cd/m^2
$L_{wall3;avg}$	53.05 cd/m^2
$L_{wall4;avg}$	60.77 cd/m^2
Valid Trials	479
Total Trials	21821
Total Opt.Time	0:22:28

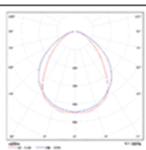
Table B.14. Layout and output of OptimLUM for small room with Luminaire 14.

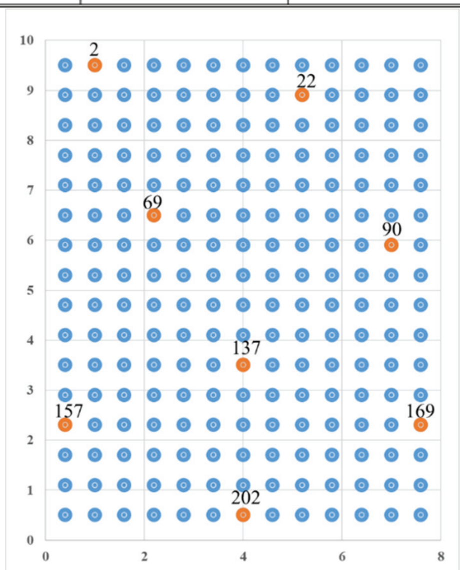
14	PHILIPS BBS560 1xLED35S/840 AC-MLO-C (dayzone)			3500 lumen	103 lm/W	34 W



E_{avg}	499.59 lux
U	0.15
E_{wall1}/E_{work}	0.47
E_{wall2}/E_{work}	0.52
E_{wall3}/E_{work}	0.53
E_{wall4}/E_{work}	0.65
$L_{wall1;avg}$	45.15 cd/m^2
$L_{wall2;avg}$	49.83 cd/m^2
$L_{wall3;avg}$	50.21 cd/m^2
$L_{wall4;avg}$	61.81 cd/m^2
Valid Trials	128
Total Trials	21270
Total Opt.Time	0:32:36

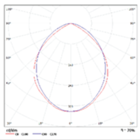
Table B.15. Layout and output of OptimLUM for medium room with Luminaire 1.

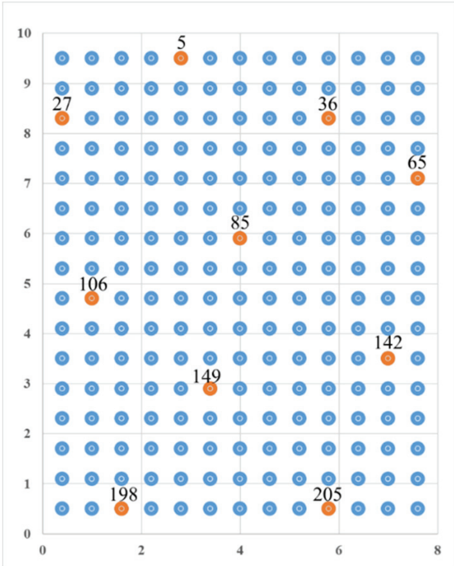
1	PHILIPS CoreLine Surface-mounted (SM120V LED37S/840 PSU W60L60)			3700 lumen	93 lm/W	42 W



E_{avg}	375.62 lux
U	0.15
E_{wall1}/E_{work}	0.70
E_{wall2}/E_{work}	0.76
E_{wall3}/E_{work}	0.75
E_{wall4}/E_{work}	0.73
$L_{wall1;avg}$	50.13 cd/m^2
$L_{wall2;avg}$	54.36 cd/m^2
$L_{wall3;avg}$	53.55 cd/m^2
$L_{wall4;avg}$	52.65 cd/m^2
Valid Trials	877
Total Trials	56474
Total Opt.Time	1:52:28

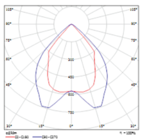
Table B.16. Layout and output of OptimLUM for medium room with Luminaire 2.

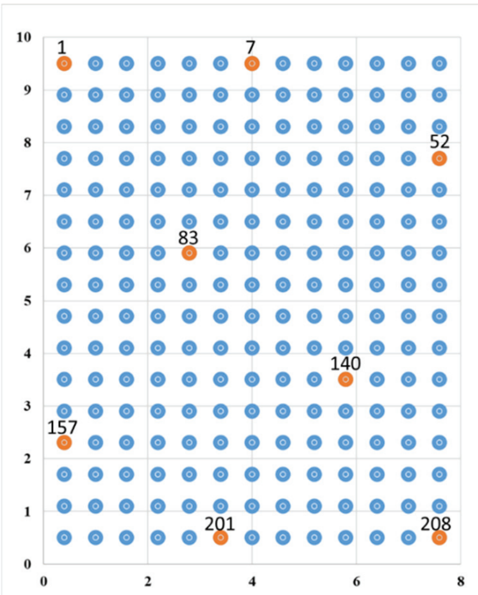
2	PHILIPS Centura 2 (TCS160 4xTL-D18W HF C3)			3780 lumen	209 lm/W	69.5 W



E_{avg}	389.05 lux
U	0.10
E_{wall1}/E_{work}	0.79
E_{wall2}/E_{work}	0.71
E_{wall3}/E_{work}	0.69
E_{wall4}/E_{work}	0.70
$L_{wall1;avg}$	59.03 cd/m^2
$L_{wall2;avg}$	52.63 cd/m^2
$L_{wall3;avg}$	51.47 cd/m^2
$L_{wall4;avg}$	52.50 cd/m^2
Valid Trials	770
Total Trials	27012
Total Opt.Time	00:50:25

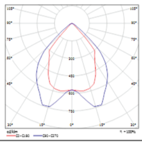
Table B.17. Layout and output of OptimLUM for medium room with eight Luminaire 3.

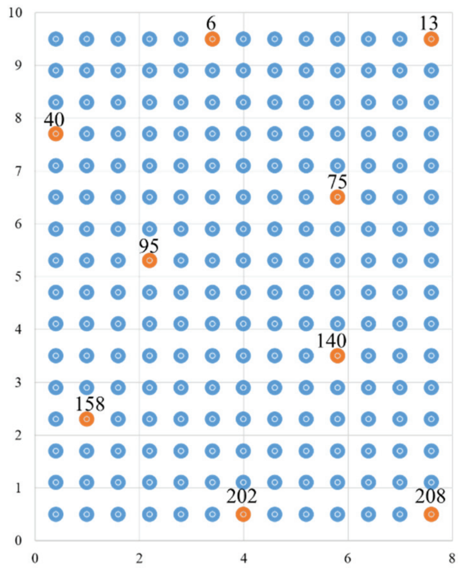
3	OSRAM SITECO 51MT1LV0JHGEB B02 Taris®2			3930 lumen	131 lm/W	30 W



E_{avg}	392.12 lux
U	0.29
E_{wall1}/E_{work}	0.67
E_{wall2}/E_{work}	0.70
E_{wall3}/E_{work}	0.67
E_{wall4}/E_{work}	0.69
$L_{wall1;avg}$	50.27 cd/m^2
$L_{wall2;avg}$	52.23 cd/m^2
$L_{wall3;avg}$	50.19 cd/m^2
$L_{wall4;avg}$	52.03 cd/m^2
Valid Trials	1116
Total Trials	52111
Total Opt.Time	1:59:00

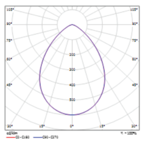
Table B.18. Layout and output of OptimLUM for medium room with nine Luminaire 3.

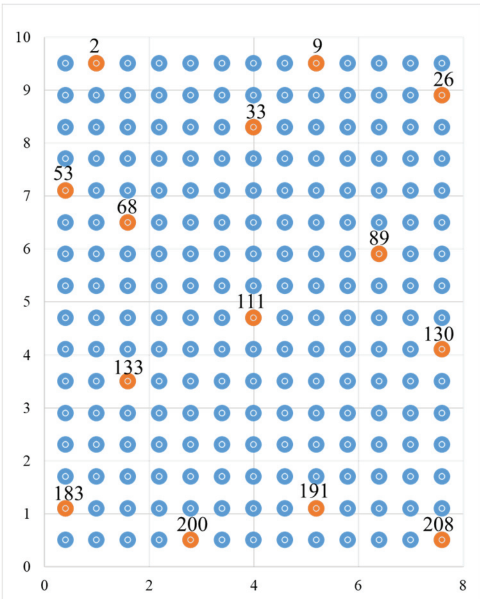
3	OSRAM SITECO 51MT1LV0JHGEB B02 Taris®2			3930 lumen	131 lm/W	30 W



E_{avg}	471.93 lux
U	0.20
E_{wall1}/E_{work}	0.59
E_{wall2}/E_{work}	0.57
E_{wall3}/E_{work}	0.59
E_{wall4}/E_{work}	0.56
$L_{wall1;avg}$	53.43 cd/m^2
$L_{wall2;avg}$	51.54 cd/m^2
$L_{wall3;avg}$	53.28 cd/m^2
$L_{wall4;avg}$	50.51 cd/m^2
Valid Trials	2370
Total Trials	42169
Total Opt.Time	1:38:19

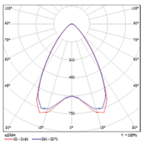
Table B.19. Layout and output of OptimLUM for medium room with Luminaire 4.

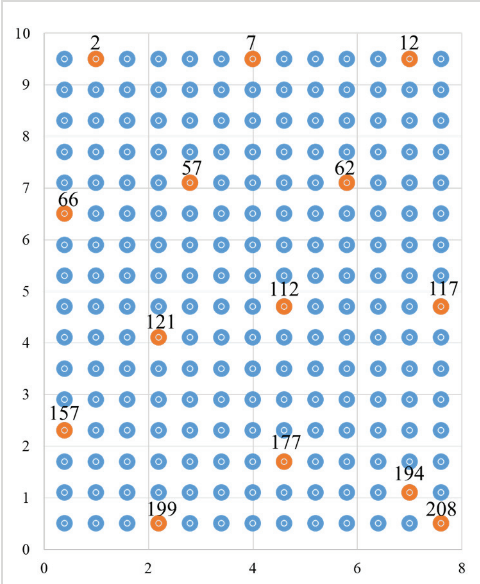
4	OSRAM SITECO 0DX11A7833S LEDVALUX® XL (Lunis)			1970 lumen	104 lm/W	19 W



E_{avg}	354.30 lux
U	0.12
E_{wall1}/E_{work}	0.75
E_{wall2}/E_{work}	0.77
E_{wall3}/E_{work}	0.75
E_{wall4}/E_{work}	0.75
$L_{wall1;avg}$	50.80 cd/m^2
$L_{wall2;avg}$	52.41 cd/m^2
$L_{wall3;avg}$	50.77 cd/m^2
$L_{wall4;avg}$	50.92 cd/m^2
Valid Trials	308
Total Trials	42373
Total Opt.Time	1:32:47

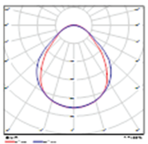
Table B.20. Layout and output of OptimLUM for medium room with Luminaire 5.

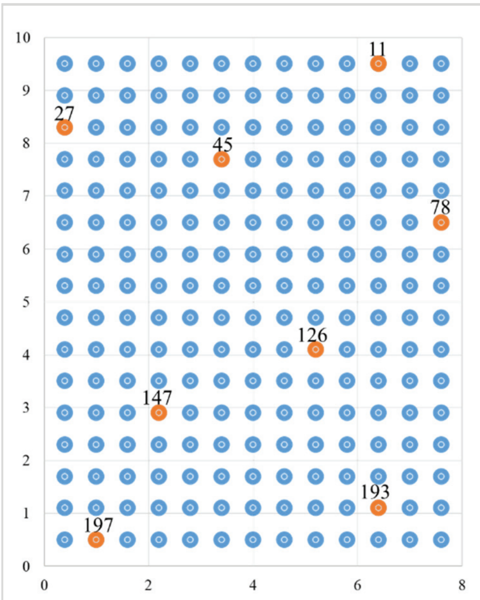
5	OSRAM SITECO 5MZ212D03WA Scriptus®			2195 lumen	127 lm/W	17.3 W



E_{avg}	410.27 lux
U	0.15
E_{wall1}/E_{work}	0.64
E_{wall2}/E_{work}	0.65
E_{wall3}/E_{work}	0.72
E_{wall4}/E_{work}	0.64
$L_{wall1;avg}$	50.02 cd/m^2
$L_{wall2;avg}$	50.59 cd/m^2
$L_{wall3;avg}$	56.22 cd/m^2
$L_{wall4;avg}$	50.63 cd/m^2
Valid Trials	2373
Total Trials	73546
Total Opt.Time	2:49:02

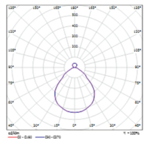
Table B.21. Layout and output of OptimLUM for medium room with Luminaire 6.

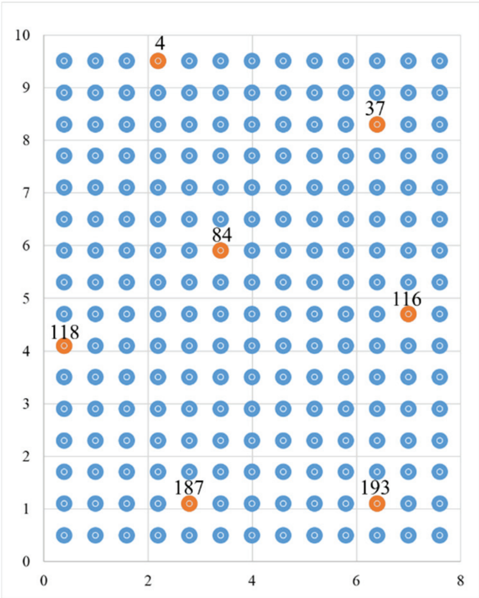
6	Zumtobel 42185186 MLevo AA LED3600-840 Q LDO SR			3450 lumen	115 lm/W	30.4 W



E_{avg}	345.06 lux
U	0.18
E_{wall1}/E_{work}	0.80
E_{wall2}/E_{work}	0.79
E_{wall3}/E_{work}	0.77
E_{wall4}/E_{work}	0.77
$L_{wall1;avg}$	52.68 cd/m^2
$L_{wall2;avg}$	51.88 cd/m^2
$L_{wall3;avg}$	50.43 cd/m^2
$L_{wall4;avg}$	50.62 cd/m^2
Valid Trials	52
Total Trials	38416
Total Opt.Time	1:27:16

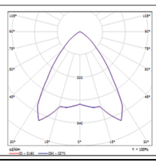
Table B.22. Layout and output of OptimLUM for medium room with Luminaire 7.

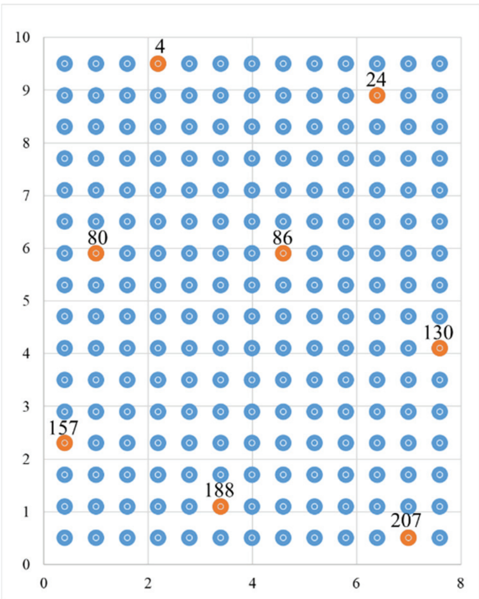
7	Zumtobel 42184475 LFE DI LED4600-840 Q LDO ASH1 SRE (Light Fields)			4530 lumen	121 lm/W	37.5 W



E_{avg}	388.18 lux
U	0.17
E_{wall1}/E_{work}	0.70
E_{wall2}/E_{work}	0.68
E_{wall3}/E_{work}	0.77
E_{wall4}/E_{work}	0.72
$L_{wall1;avg}$	52.17 cd/m^2
$L_{wall2;avg}$	50.19 cd/m^2
$L_{wall3;avg}$	57.43 cd/m^2
$L_{wall4;avg}$	53.69 cd/m^2
Valid Trials	855
Total Trials	39339
Total Opt.Time	1:33:35

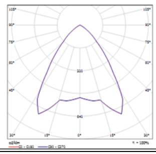
Table B.23. Layout and output of OptimLUM for medium room with eight Luminaire 8.

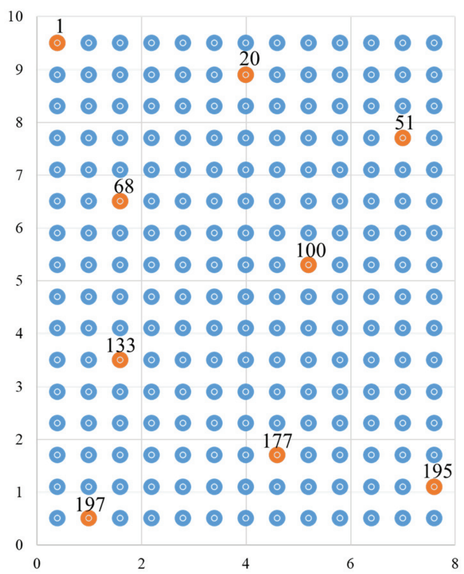
8	Zumtobel 42182361 MIREL-L LAY LED3800-840 M600Q EVG KA			3740 lumen	134 lm/W	28 W



E_{avg}	397.07 lux
U	0.27
E_{wall1}/E_{work}	0.68
E_{wall2}/E_{work}	0.68
E_{wall3}/E_{work}	0.69
E_{wall4}/E_{work}	0.69
$L_{wall1;avg}$	51.78 cd/m^2
$L_{wall2;avg}$	51.28 cd/m^2
$L_{wall3;avg}$	52.52 cd/m^2
$L_{wall4;avg}$	52.42 cd/m^2
Valid Trials	864
Total Trials	70108
Total Opt.Time	2:41:36

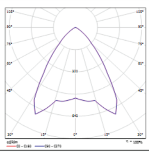
Table B.24. Layout and output of OptimLUM for medium room with nine Luminaire 8.

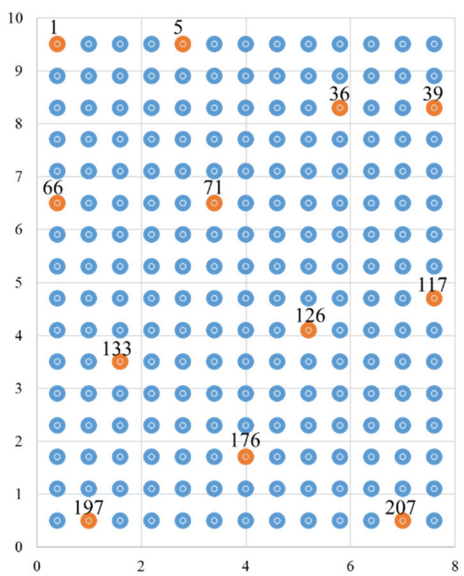
8	Zumtobel 42182361 MIREL-L LAY LED3800-840 M600Q EVG KA			3740 lumen	134 lm/W	28 W



E_{avg}	468.12 lux
U	0.19
E_{wall1}/E_{work}	0.61
E_{wall2}/E_{work}	0.59
E_{wall3}/E_{work}	0.57
E_{wall4}/E_{work}	0.59
$L_{wall1;avg}$	54.34 cd/m^2
$L_{wall2;avg}$	52.44 cd/m^2
$L_{wall3;avg}$	51.05 cd/m^2
$L_{wall4;avg}$	52.99 cd/m^2
Valid Trials	2039
Total Trials	26993
Total Opt.Time	1:00:34

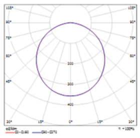
Table B.25. Layout and output of OptimLUM for medium room with Luminaire 9.

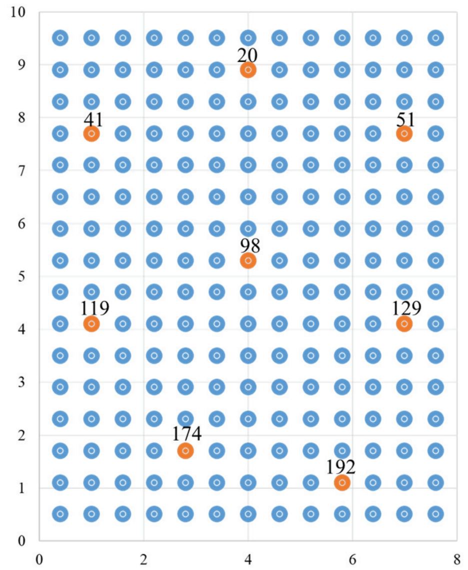
9	Zumtobel 42925916 MIREL-L LAY LED2800-830 M600Q LDO KA			2600 lumen	130 lm/W	20 W



E_{avg}	417.49 lux
U	0.12
E_{wall1}/E_{work}	0.65
E_{wall2}/E_{work}	0.70
E_{wall3}/E_{work}	0.66
E_{wall4}/E_{work}	0.67
$L_{wall1;avg}$	51.90 cd/m^2
$L_{wall2;avg}$	55.48 cd/m^2
$L_{wall3;avg}$	52.68 cd/m^2
$L_{wall4;avg}$	53.88 cd/m^2
Valid Trials	1573
Total Trials	33076
Total Opt.Time	1:07:13

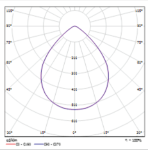
Table B.26. Layout and output of OptimLUM for medium room with Luminaire 10.

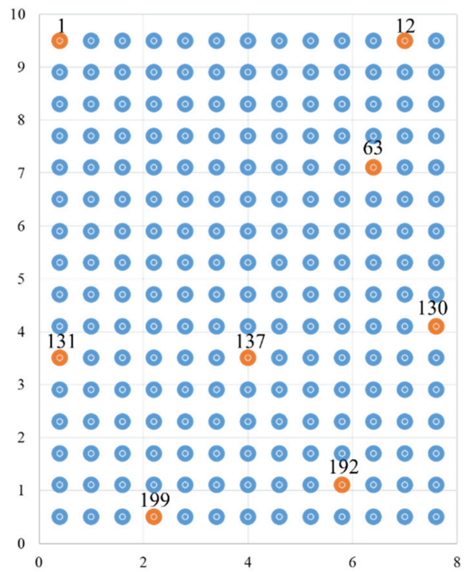
10	Zumtobel 42182369 MIREL-O NIV LED3800-840 M600Q EVG KA			3710 lumen	139 lm/W	26.7 W



E_{avg}	384.31 lux
U	0.11
E_{wall1}/E_{work}	0.71
E_{wall2}/E_{work}	0.80
E_{wall3}/E_{work}	0.70
E_{wall4}/E_{work}	0.78
$L_{wall1;avg}$	51.80 cd/m^2
$L_{wall2;avg}$	58.38 cd/m^2
$L_{wall3;avg}$	51.13 cd/m^2
$L_{wall4;avg}$	57.43 cd/m^2
Valid Trials	876
Total Trials	42605
Total Opt.Time	1:28:51

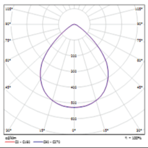
Table B.27. Layout and output of OptimLUM for medium room with eight Luminaire 11.

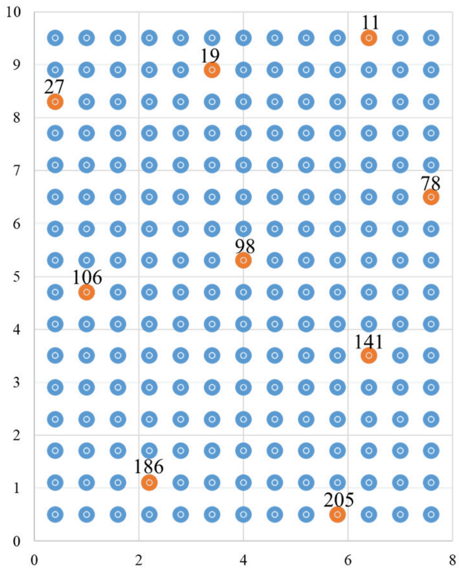
11	PHILIPS RC461B G2 PSD W60L60 1xLED34S/840 (smartbalance)			3400 lumen	142 lm/W	25 W



E_{avg}	338.93 lux
U	0.29
E_{wall1}/E_{work}	0.77
E_{wall2}/E_{work}	0.78
E_{wall3}/E_{work}	0.78
E_{wall4}/E_{work}	0.79
$L_{wall1;avg}$	50.00 cd/m^2
$L_{wall2;avg}$	50.41 cd/m^2
$L_{wall3;avg}$	50.43 cd/m^2
$L_{wall4;avg}$	51.72 cd/m^2
Valid Trials	57
Total Trials	133178
Total Opt.Time	4:47:55

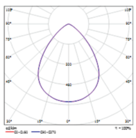
Table B.28. Layout and output of OptimLUM for medium room with nine Luminaire 11.

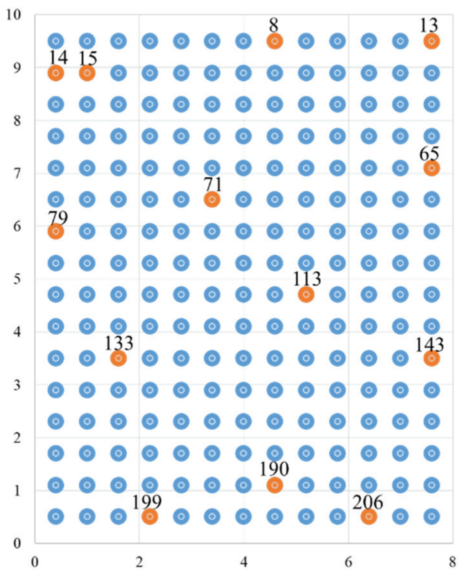
11	PHILIPS RC461B G2 PSD W60L60 1xLED34S/840 (smartbalance)			3400 lumen	142 lm/W	25 W



E_{avg}	406.27 lux
U	0.14
E_{wall1}/E_{work}	0.67
E_{wall2}/E_{work}	0.65
E_{wall3}/E_{work}	0.71
E_{wall4}/E_{work}	0.66
$L_{wall1;avg}$	52.13 cd/m^2
$L_{wall2;avg}$	50.30 cd/m^2
$L_{wall3;avg}$	54.83 cd/m^2
$L_{wall4;avg}$	51.48 cd/m^2
Valid Trials	982
Total Trials	42071
Total Opt.Time	1:15:03

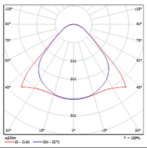
Table B.29. Layout and output of OptimLUM for medium room with Luminaire 12.

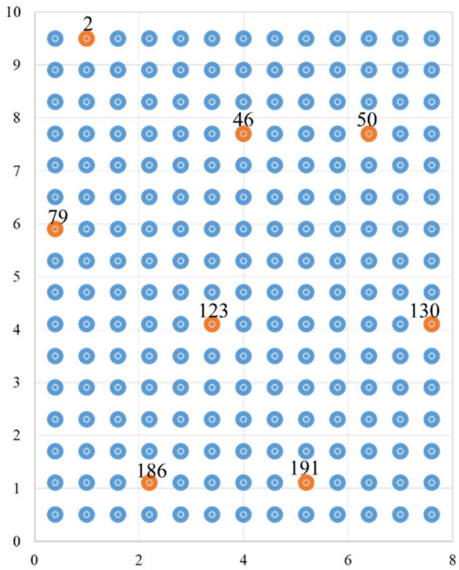
12	PHILIPS DN570B PSED-E 1xLED20S/830 C PG (LuxSpace)			2100 lumen	111 lm/W	19 W



E_{avg}	351.27 lux
U	0.15
E_{wall1}/E_{work}	0.75
E_{wall2}/E_{work}	0.79
E_{wall3}/E_{work}	0.75
E_{wall4}/E_{work}	0.74
$L_{wall1;avg}$	50.38 cd/m^2
$L_{wall2;avg}$	53.16 cd/m^2
$L_{wall3;avg}$	50.28 cd/m^2
$L_{wall4;avg}$	50.17 cd/m^2
Valid Trials	319
Total Trials	56549
Total Opt.Time	2:13:05

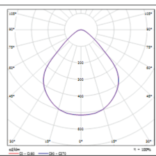
Table B.30. Layout and output of OptimLUM for medium room with Luminaire 13.

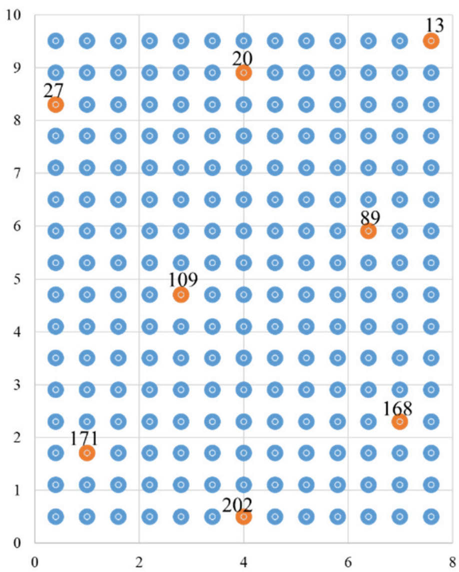
13	PHILIPS SP480P W24L134 1xLED35S/830 ACC-MLO (smartbalance)			3500 lumen	119 lm/W	37 W



E_{avg}	368.72 lux
U	0.13
E_{wall1}/E_{work}	0.71
E_{wall2}/E_{work}	0.75
E_{wall3}/E_{work}	0.72
E_{wall4}/E_{work}	0.80
$L_{wall1;avg}$	50.27 cd/m^2
$L_{wall2;avg}$	53.15 cd/m^2
$L_{wall3;avg}$	50.73 cd/m^2
$L_{wall4;avg}$	56.37 cd/m^2
Valid Trials	288
Total Trials	32770
Total Opt.Time	0:59:55

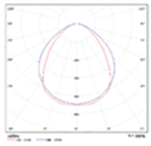
Table B.31. Layout and output of OptimLUM for medium room with Luminaire 14.

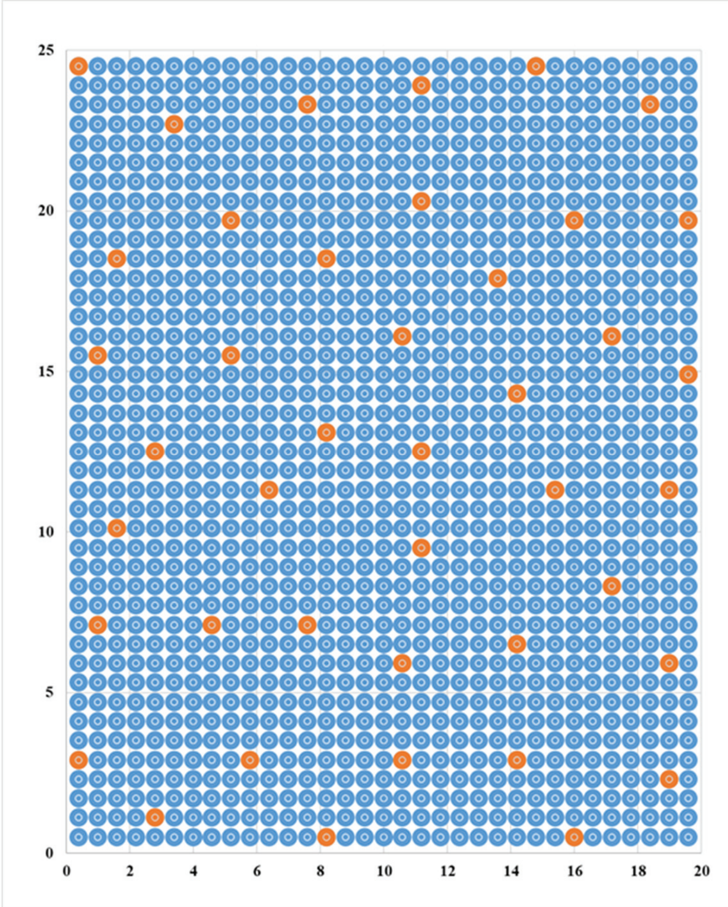
14	PHILIPS BBS560 1xLED35S/840 AC-MLO-C (dayzone)			3500 lumen	103 lm/W	34 W



E_{avg}	362.92 lux
U	0.16
E_{wall1}/E_{work}	0.72
E_{wall2}/E_{work}	0.73
E_{wall3}/E_{work}	0.74
E_{wall4}/E_{work}	0.74
$L_{wall1;avg}$	50.13 cd/m^2
$L_{wall2;avg}$	50.83 cd/m^2
$L_{wall3;avg}$	51.22 cd/m^2
$L_{wall4;avg}$	51.24 cd/m^2
Valid Trials	198
Total Trials	44122
Total Opt.Time	1:39:22

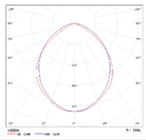
Table B.32. Layout and output of OptimLUM for large room with Luminaire 1.

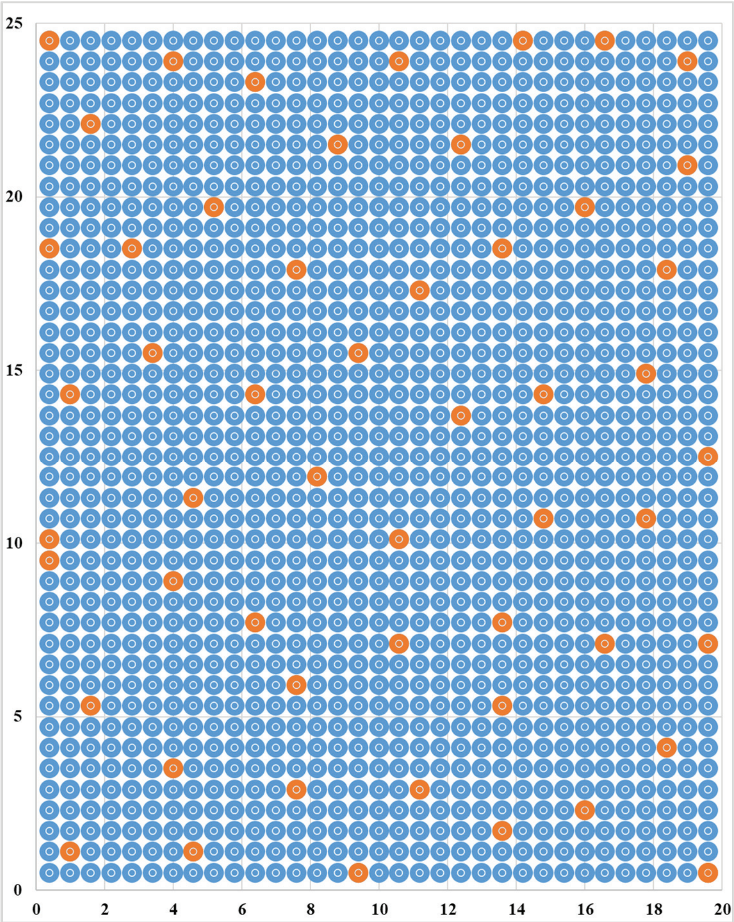
1	PHILIPS CoreLine Surface-mounted (SM120V LED37S/840 PSU W60L60)			3700 lumen	93 lm/W	42 W



E_{avg}	385.13 lux
U	0.16
E_{wall1}/E_{work}	0.69
E_{wall2}/E_{work}	0.77
E_{wall3}/E_{work}	0.68
E_{wall4}/E_{work}	0.71
$L_{wall1;avg}$	50.65 cd/m^2
$L_{wall2;avg}$	56.62 cd/m^2
$L_{wall3;avg}$	50.30 cd/m^2
$L_{wall4;avg}$	52.47 cd/m^2
Valid Trials	11650
Total Trials	154192
Total Opt.Time	71:59:35

Table B.33. Layout and output of OptimLUM for large room with Luminaire 2.

2	PHILIPS Centura 2 (TCS160 4xTL-D18W HF C3)			3780 lumen	209 lm/W	69.5 W



E_{avg}	396.07 lux
U	0.11
E_{wall1}/E_{work}	0.71
E_{wall2}/E_{work}	0.75
E_{wall3}/E_{work}	0.68
E_{wall4}/E_{work}	0.67
$L_{wall1;avg}$	52.68 cd/m^2
$L_{wall2;avg}$	57.20 cd/m^2
$L_{wall3;avg}$	56.71 cd/m^2
$L_{wall4;avg}$	57.73 cd/m^2
Valid Trials	12100
Total Trials	146003
Total Opt.Time	67:26:47

APPENDIX C

OptimLUM- DAYLIGHT INTEGRATION LAYOUTS

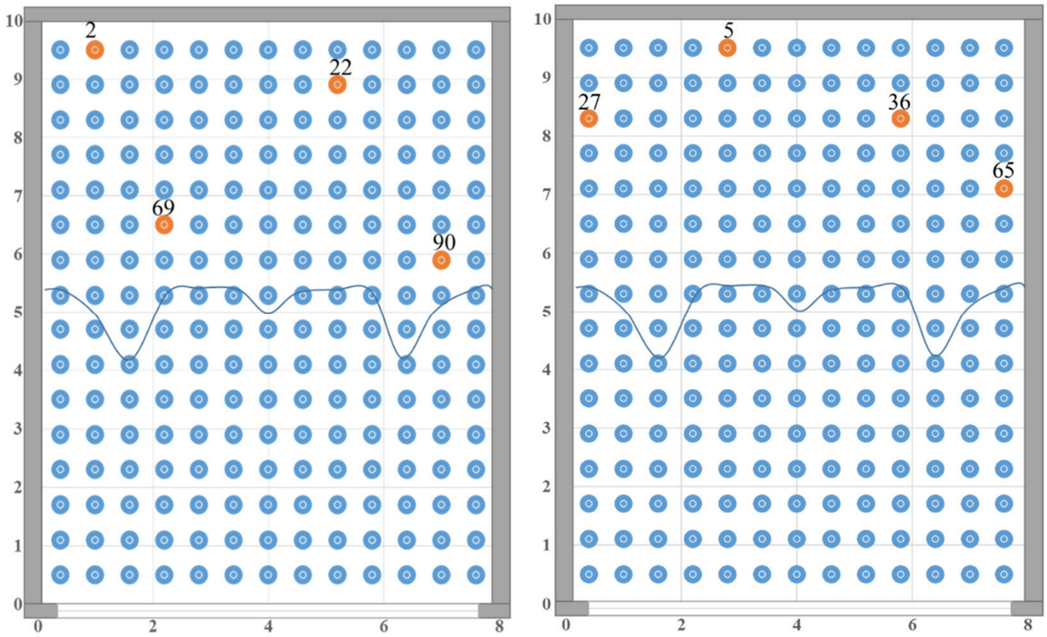


Figure C.1. OptimLUM layouts and daylight integration with luminaire 1 and 2 for medium room.

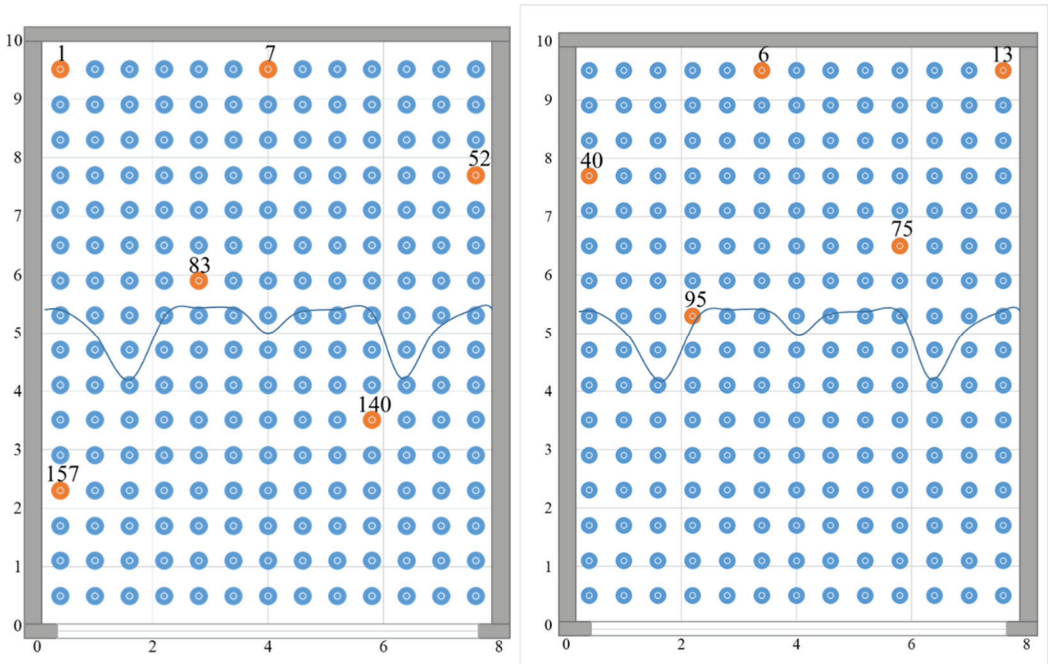


Figure C.2. OptimLUM layouts and daylight integration with eight and nine number of luminaire 3 for medium room.

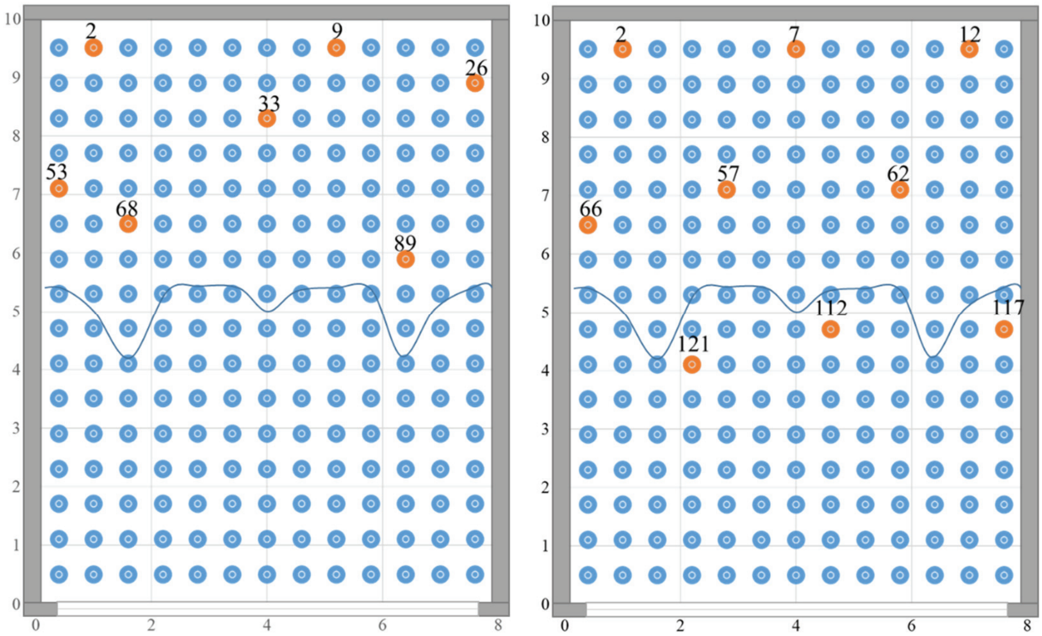


Figure C.3. OptimLUM layouts and daylight integration with luminaire 4 and 5 for medium room.

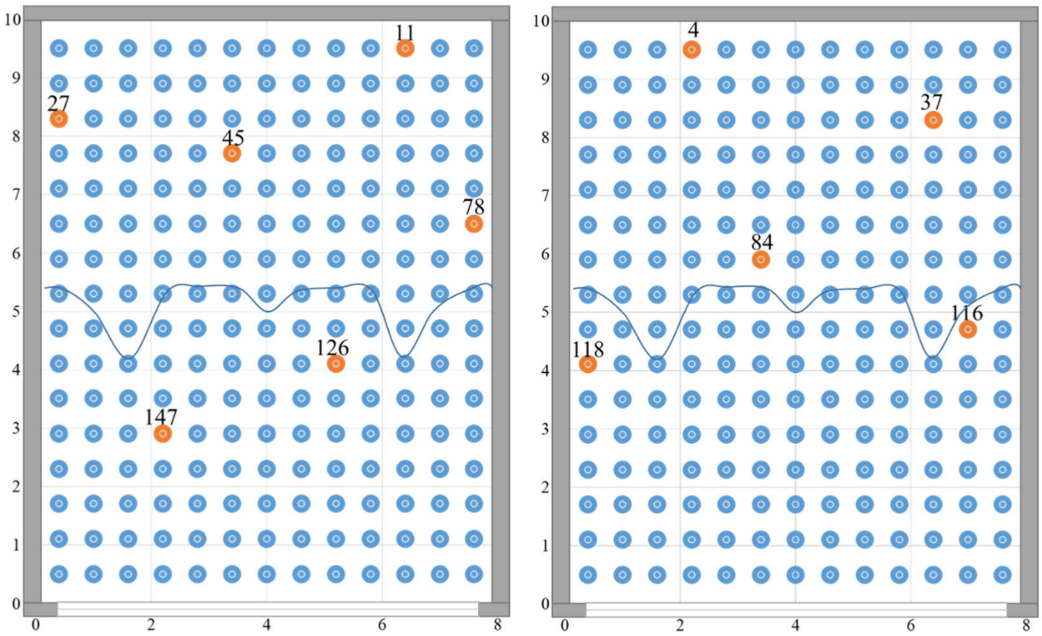


Figure C.4. OptimLUM layouts and daylight integration with luminaire 6 and 7 for medium room.

Figure C.5. OptimLUM layouts and daylight integration with eight and nine number of luminaire 8 for medium room.

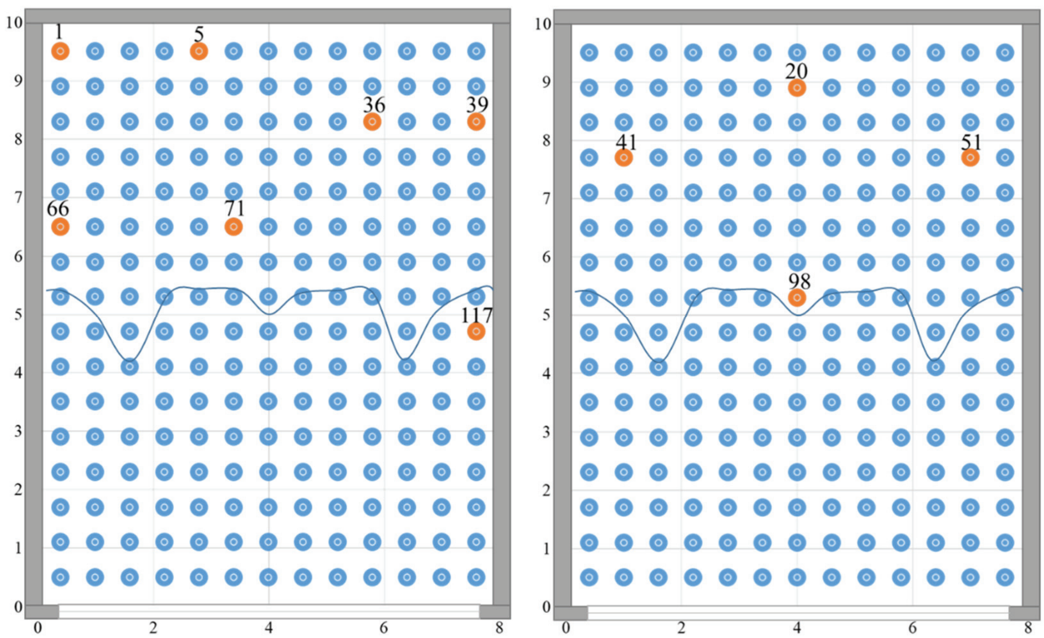


Figure C.6. OptimLUM layouts and daylight integration with luminaire 9 and 10 for medium room.

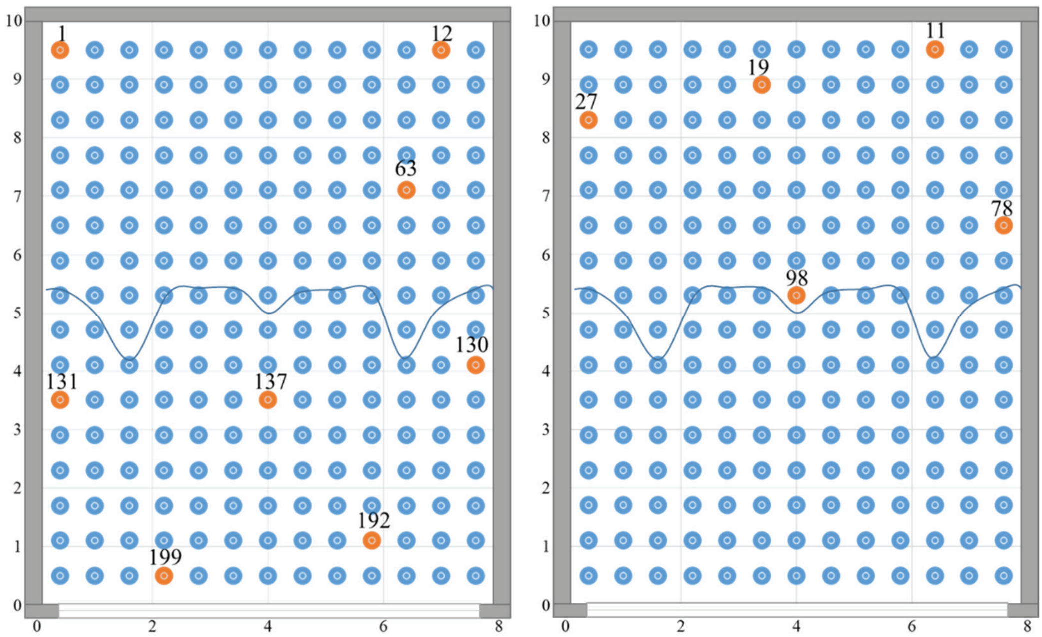


Figure C.7. OptimLUM layouts and daylight integration with eight and nine number of luminaire 11 for medium room.

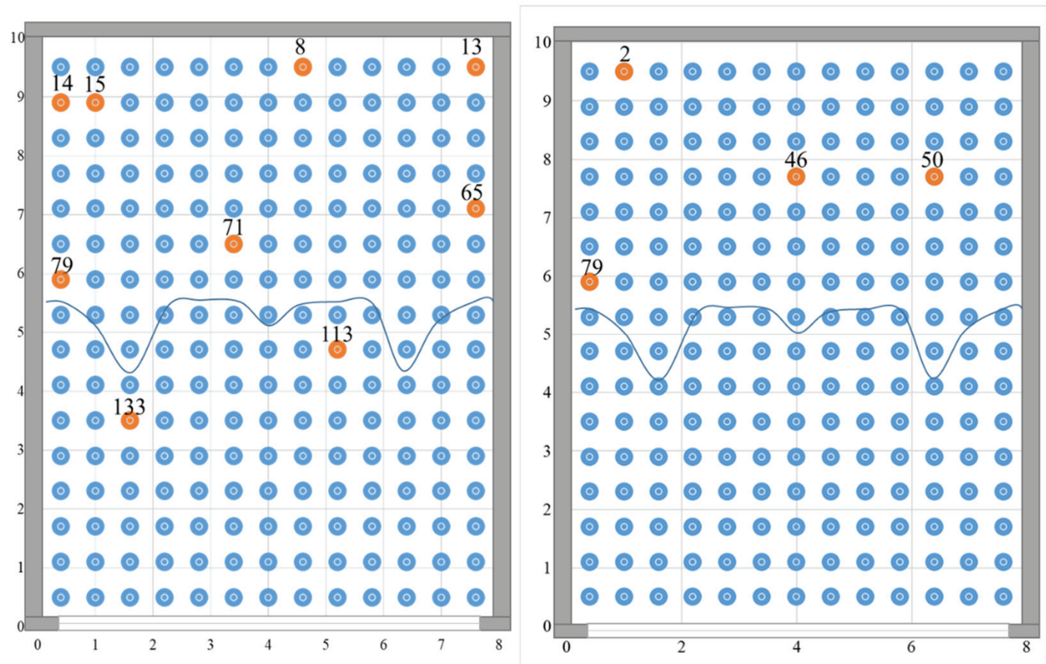


Figure C.8. OptimLUM layouts and daylight integration with luminaire 12 and 13 for medium room.

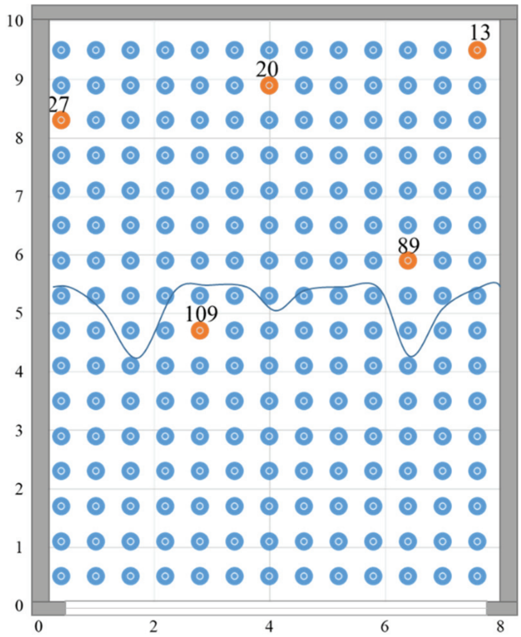


Figure C.9. OptimLUM layout and daylight integration with luminaire14 for medium room.