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UNIVERSITY

Ansis Avotiņš

RESEARCH AND DEVELOPMENT OF SMART LED LIGHTING SYSTEM

Summary of the Doctoral Thesis



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RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering
Institute of Industrial Electronics and Electrical Engineering

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Doctoral Student of the Study Programme
“Computerised Control of Electrical Technologies”

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph.D.) is my own.

I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Ansis Avotiņš _____ (signature)

Date: _____

The Doctoral Thesis has been prepared as a thematically united collection of scientific publications. It consists of summary and 27 publications and 1 WIPO patent. Publications have been written in English. The total number of publication pages is 290.

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General Overview of the Thesis

Topicality of the research

During the spring summit of the European Council in 2007, EU 20-20-20 Directive 2012/27/EU was passed [1]. From 1990 to 2018, the greenhouse gas emissions decreased by 23 % [2], according to the information in Eurostat database, the total air pollution and CO₂ emissions of 27 EU Member States from 2010 to 2019 decreased on average by 1.57 % annually. The key challenge of the EU Green Deal, that was passed in 2019 [2], is to provide that the EU greenhouse gas emissions decrease by 50–55 % by 2030, compared to the level of 1990. Since 2012, Latvia has used resources of the Emission Allowance Auction Instrument (EKII) to co-finance street lighting modernisation projects (23), and smart urban solutions are introduced that are based on a more comprehensive use of information and communication technologies (ICT), which increase the energy efficiency significantly, reduce emissions and improve traffic safety. Based on Eurostat data, the death toll of street accidents in Latvia per 100,000 inhabitants has decreased from 26.8 (in 2000) to 7.7 (in 2018) that indirectly correlates with the improved availability of street lighting in towns. In 2012, Latvia spent 79 GWh/per year for street lighting that, as a result of increased electricity tariff, amounted to EUR 11.34 million (26).

Due to the European energy market liberalisation increase in the number of local energy networks, integration of renewable energy resources, spread of cogeneration and micro production (micro networks, virtual electricity facilities) and demand from new users, more modern monitoring, control and electronic electricity trade technologies are necessary that would impact the existing street lighting systems, if implemented.

Based on the European Construction Technology Platform (ECTP) data, 80 % of Europeans live in cities [3] that are the end users of public lighting systems. Infrastructure in the city centres, especially in Eastern Europe, is outdated, therefore, when rebuilding these areas, the cities should focus on more efficient use of energy and possible integration of alternative energy sources [4]. To ensure street lighting in a city in Europe, the total electricity consumption expenditure on average is 6–7 %, but in some cases it can reach even 60 % of the total budget of local municipality [5]. Improvement of the energy efficiency of the end user, in this case in the street lighting system and LED luminaires, creates additional savings for the producers, as it is known that significant losses in the electricity production are common in transmission (2 %) and distribution (8 %) processes. LED luminaires currently are the key solution aimed at increasing the efficiency of street lighting systems, and with implementation of movement sensors and efficient light regulating algorithms, the smart street lighting systems have high future potential, creating new functions and opportunities for smart cities that would consequently create significant economic benefits.

Main hypotheses and aims

Hypotheses

1. It is possible to save up to 50 % on electricity with smart street lighting systems equipped with LED luminaires.
2. It is possible to save additional 10 % on electricity with smart street lighting systems equipped with LED luminaires and motion sensors.
3. Smart lighting control system with dynamic control algorithm can improve lighting quality and traffic safety on streets.

Aims

1. Perform analysis of lighting systems and develop their architecture comparison.
2. Develop a new smart LED lighting system.
3. Experimentally prove advantages of smart LED lighting systems.
4. Optimise new smart LED lighting system control methods.

Research tools and methods

MatLab and MS-Excel computer programs were used to simplify the theoretical calculations and graphically represent the obtained results. In addition to modelling and development of electrical circuits, OrCAD and LTspice software were used. DiaLux lighting calculation software was used to simulate and determine the optical quality of the lighting. For ZigBee protocol tests, Microchip ZENA 3.0 Network Analyzer software and transceivers were used.

The verification of the obtained theoretical results in laboratory conditions was performed with the help of experiments in a laboratory specially adapted for this purpose and in a specially built laboratory stand. The stand is designed with dimensions of 2.2 m × 2.2 m × 3 m, and the LED luminaires under study were placed in it. The stand was covered with black curtain material, thus providing optical measurements that are not affected by external lighting. Measurements were performed using Hagner digital lux meter EC1, LMK MobileAir lighting photo camera able to take luminance photography, and Avantes VIS-NIR spectrometer. An adjustable DC power supply or autotransformer, function generator (for control signals), power analyser, oscilloscopes, thermal imager Fluke Ti10 and laser temperature meter were used to test the electrical parameters both indoors and outdoors.

Scientific novelty

1. New wireless data transmission communication modules, based on ZigBee and radio signals, integrated in each controlled LED luminaire to determine real-time power consumption, have been integrated and tested in real conditions of the existing street lighting system.
2. A new decentralized street intelligent lighting system with dimmable LED luminaires, motion sensors and real-time wireless data transmission has been developed and integrated into the real urban street lighting system.
3. A new method for real-time monitoring of street lighting electricity consumption has been developed.
4. Novel traffic intensity adaptive control algorithm for lighting system and LED luminaries has been developed.

Practical novelties

1. A new ZigBee protocol wireless communication control module has been developed for the regulation of LED luminaires, which has been installed at the testing Pilot-Site in the RTU parking lot (*Meža Street*), replacing the existing sodium high-pressure lamp luminaires and thus increasing energy efficiency.
2. A new intelligent LED lighting system has been installed for pedestrians in the RTU campus territory in *Kīpsala* and for vehicle traffic on *Zunda krastmala Street*, which has resulted in a significant reduction in electricity consumption.
3. A new system and method for real-time monitoring of electricity consumption (WIPO patent) was developed and adapted to measure the electricity consumption of LED luminaires.

Practical significance of the work

In the course of the work, in-depth knowledge of intelligent street lighting systems with LED luminaires was acquired, which allowed to provide expertise services to several Latvian municipalities and institutions of Ministry of Environmental Protection and Regional Development of the Republic of Latvia.

New product has been developed – dimmable LED luminary with power of 56 W.

A novel adaptive control algorithm for maximum energy efficiency increase has been developed which has the necessary lighting quality and traffic safety in terms of lighting parameters.

In the course of the work, experimental tests of LED lighting systems were carried out in several Pilot Sites, which allowed to evaluate the reduction of power consumption of large number of lighting luminary in real lighting systems and compliance of lighting quality parameters to regulatory norms and initial results of Dialux modelling programs and overall efficiency of the control system.

Approbation of the Thesis

74 publications and 2 patents were created in total. The summary of the Thesis consists of 27 publications and 1 WIPO patent. List of publications and patent:

1. **A. Avotins**, L. R. Adrian, R. Porins, P. Apse-Apsitis, L. Ribickis. Smart City Street Lighting System Quality and Control Issues to Increase Energy Efficiency and Safety. *Baltic Journal of Road and Bridge Engineering*, 2021, Volume 16, Issue 4, pp. 28–57.
2. L.R. Adrian, **A. Avotins**, D. Repole, O. Tetervenoks. Development of New Radar and Pyroelectric Sensors for Road Safety Increase in Cloud-Based Multi-Agent Control Application. *Baltic Journal of Road and Bridge Engineering*, 2021, Volume 16, Issue 4, pp. 76–107.
3. **A. Avotins**, O. Tetervenoks, L. R. Adrian and A. Severdaks, “Traffic Intensity Adaptive Street Lighting Control,” *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, 2021, pp. 1–6.
4. K. Kviesis, L. R. Adrian, **A. Avotins**, O. Tetervenoks and D. Repole, “MAS Concept for PIR Sensor-Based Lighting System Control Applications,” *2020 IEEE 8th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, 2021, pp. 1–5.
5. R. Porins, P. Apse-Apsitis and **A. Avotins**, “PIR-Sensor Based Street Lighting System Control,” *2020 IEEE 8th Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE)*, 2021.
6. Apse-Apsitis, P., **Avotins, A.**, Graudone, J., Porins, R. RGB based sensor for semi-spherical light measurements. *Engineering for Rural Development*, 2020, 19, pp. 1242-1247.
7. Tetervenoks, O., **Avotins, A.**, Fedorjana, N., Kluga, A., Krasts, V. Potential Role of Street Lighting System for Safety Enhancement on the Roads in Future. In: *2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2019): Conference Proceedings, Latvia, Riga, 7-9 October 2019*, pp. 349-353. e-ISBN 978-1-7281-3942-5.
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e-ISBN 978-90-75815-27-6.

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Introduction

In the course of evolution, humans have invented different artificial lighting technologies, however, as artificial lighting requires different energy resources, energy saving [1]-[4] is the key driver for the evolution of lighting technologies [5], [6]. Currently, in the area of artificial lighting, a completely new light emitting technology, LED (Light-Emitting Diode), is in the spotlight in the world. Due to the rapid development of LED technologies in the recent years, it is called the “light of the 21st century”, and the topicality of this technology was proved by the Nobel Prize in physics awarded in 2014 to Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura for inventing the energy efficient and environmentally friendly light source - blue light emitting diode (LED) [7], [8]. It served as an impulse to manufacture the power LED that is a combination of several small LEDs (in series, parallel or in a matrix) in one integrated casing (hereinafter - in a chip) that is now widely used in the street lighting system luminaries.

In the recent years, the key LED feature is used more often - by regulating current with different power supply blocks (20) or dimmers it is possible to regulate (to dim) the amount of emitted light from 0 to 100 %, and consequently it is possible to regulate the energy consumption of the LED luminary that was not possible fully for the gas discharge bulb luminaries. Therefore, with the help of LED dimming, lighting management systems are used more often (14), allowing to save 30–50 % of energy, compared to high pressure gas discharge bulb luminaries. In future, along with the development of the LED technology, power converters, communication and management systems (14), the electricity consumption might decrease even more, providing new opportunities in the development of quality and functional development of lighting systems (21), moreover, the future electricity supply might be decentralised and more equipped with ICT on several levels, therefore the term “smart grids” has been introduced. This serves as basis for the research that would allow to assess the possibility to use the smart grid approach in lighting systems.

Street lighting was introduced to increase the safety on roads and reduce road accidents, according to accident analysis in different USA cities [9], where the number of people who have died during the night is 3–4 times higher than during the natural light conditions, even if the traffic intensity decreases. Several quality standards were developed [10] for measurements and photometric parameter limits to be maintained that are accepted in many countries in the world and are continuously updated considering the developments in the area of lighting technologies.

1. Analysis of Lighting Quality Assessment Parameters

To create energy efficient street lighting system that complies with the laws and regulations [10], it is necessary to select appropriate luminary for every situation, therefore the characteristic parameters of each street have to be assessed that are of **geographic character**, namely, the width of street, number of lanes, distance between posts, height of posts, angle of luminary placement, distance from the road, reflection coefficient of road surface, etc. Generally, city streets can be divided in two groups (see Fig. 1.1):

- a) streets with constant distance between poles (usually new/reconstructed streets);
- b) streets with random distance between poles (non-reconstructed streets).

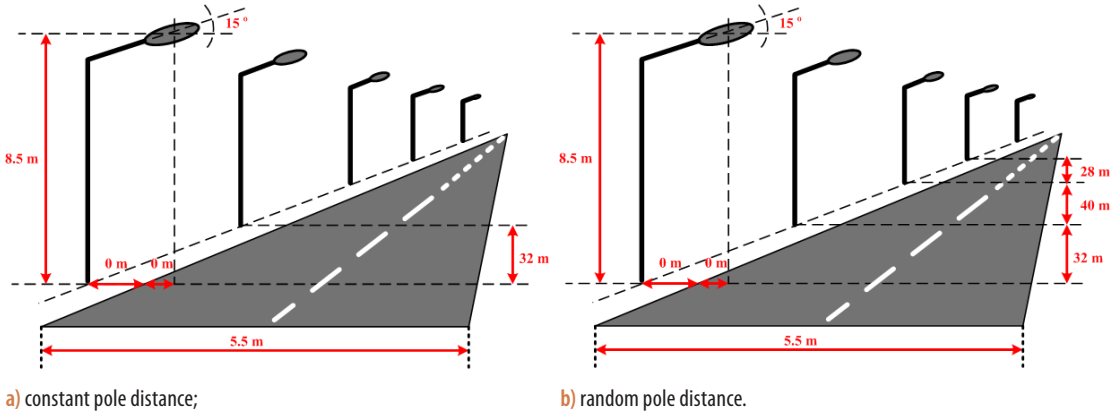


Fig. 1.1. Street profile and necessary data for Dialux calculations.

The next parameter that provides requirements for the street lighting level is types of traffic participants and traffic intensity. The selection of street lighting determines the parameter of lighting quality: minimum values of L_{av} (cd/m^2), U_0 , U_1 , f_{T1} , R_{EI} are described in the first section of the Technical Report of LVS [10] that is effective in the European Union (EU) Member States and prescribes 4 time zones during which dimming is allowed to maintain different lighting levels.

The key parameter to compare different types of lighting sources and luminaries is the total efficacy of the luminary (K , lm/W) [11], which is referred to as hL in other sources and is expressed as a proportion between the total amount of emitted light (lm , $cd \times sr$) and total power spent (P , W). Monochromatic radiation at the frequency 540×10^{12} Hz, spectral light efficiency is 683 lm/W , $K(\lambda_{555}) = 683 \text{ lm/W}$ that is equal with $683 \text{ cd} \times sr/W$ (radiated wave length λ at this frequency is approximately 555 nm).

To measure the amount of light, radiometric and photometric measurements are used (16). Radiometric measurements show the actual optical power that is determined by the consumed energy in entire lighting source spectrum. However, as human eye does not react to all wave lengths equally, a division is implemented with bell-shaped curve that is called the luminous efficiency function ($V(\lambda)$) given in Fig. 1.2.

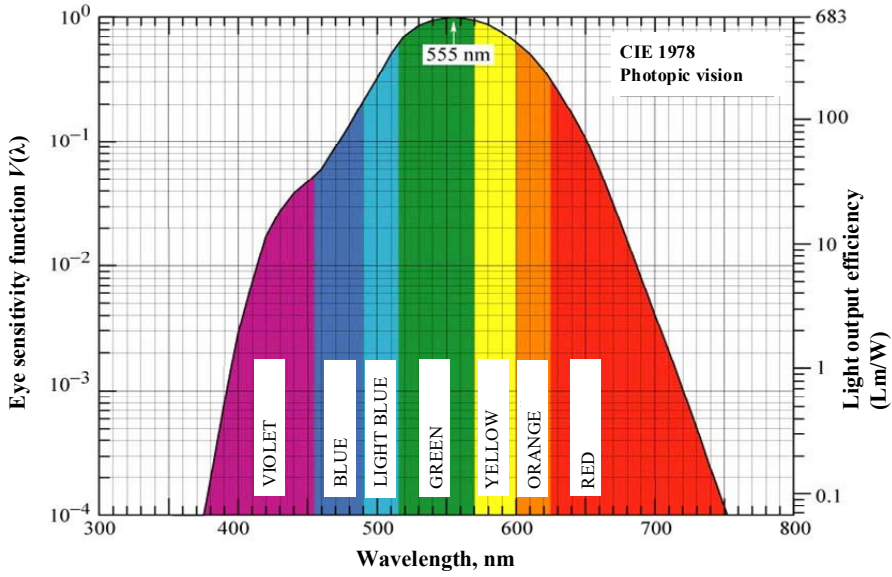


Fig. 1.2. Photopic colour vision and their maximum efficiency values.

Light return efficiency η_L can be expressed as a multiplication of spectral and electrical efficiency:

$$\eta_L = \eta_S \eta_E, \quad (1.1)$$

where η_S is spectral efficiency in the visible spectrum, lm/W,

η_E is electrical efficiency (without a measuring unit) expressed as the power of emitted light vs. consumed electrical power.

Considering the eye sensitivity function $\bar{y}(\lambda)$ spectral efficiency can be expressed as follows:

$$\eta_S = 683 \int_0^{\infty} \bar{y}(\lambda) B_\lambda d\lambda. \quad (1.2)$$

Considering that the Sun is the source of white light with surface temperature of 5800 K and it is described by normalised spectral function,

$$B_\lambda = 15 \left(\frac{hc}{\pi kT} \right)^4 \lambda^{-5} \left[e^{hc/\lambda kT} - 1 \right]^{-1} m^{-1}, \quad (1.3)$$

where λ is wave length, nm;

h is Planck constant;

c is speed of light;

k is Boltzmann constant;

T is absolutely black body temperature in Kelvins.

However, if the spectral efficiency has to be expressed in a specific wave length range, for example, in the ideal white light zone where $\lambda_{\text{blue}} = 400$ nm, but $\lambda_{\text{red}} = 700$ nm, the spectrum efficiency is calculated as follows:

$$\eta_S = 683 \frac{\int_{\lambda_{\text{blue}}}^{\lambda_{\text{red}}} \bar{y}(\lambda) B_\lambda d\lambda}{\int_{\lambda_{\text{blue}}}^{\lambda_{\text{red}}} B_\lambda d\lambda}, \quad (1.4)$$

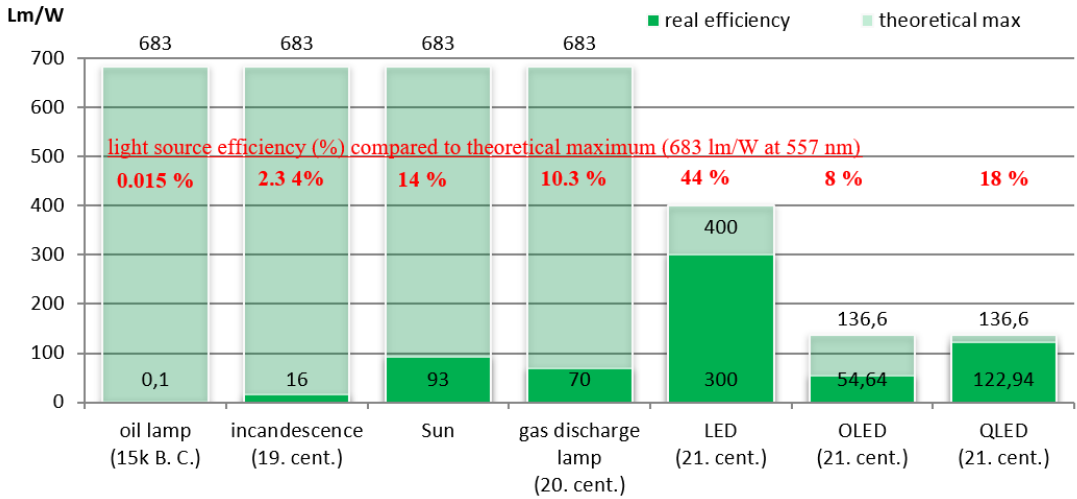


Fig. 1.3. Different light source efficiency comparison.

There are several LED chip manufacturers with different products and quality parameters (service life, efficiency, etc.), but the largest in terms of sales in 2018 are [12] given in Table 1.1; Nichia and Samsung are more focused on indoor luminaries and multimedia household appliances, however, in the area of street luminaries Osram and CREE manufactured LED chips are used most often.

Table 1.1

TOP 10 LED manufacturers by sold quantities in year 2018

No.	Manufacturer	No.	Manufacturer
1	Nichia	6	Samsung LED
2	Osram Opto Semiconductors	7	Everlight
3	Lumileds	8	CREE
4	Seoul Semiconductor	9	NationStar
5	MLS	10	Lite-On

2. LED Street Luminary Research and Development

LED luminary consists of three main elements – luminary housing, ballast, and light source. But if looking in more detail, then smart LED luminary (see Fig. 2.1) consists of light source (LED crystal/PCB) (1); reflector (2); driver/power supply (3); lens (4); heat sink/cooling system (5); housing (6); fixture to the lighting pole (7); and different sensors (8).

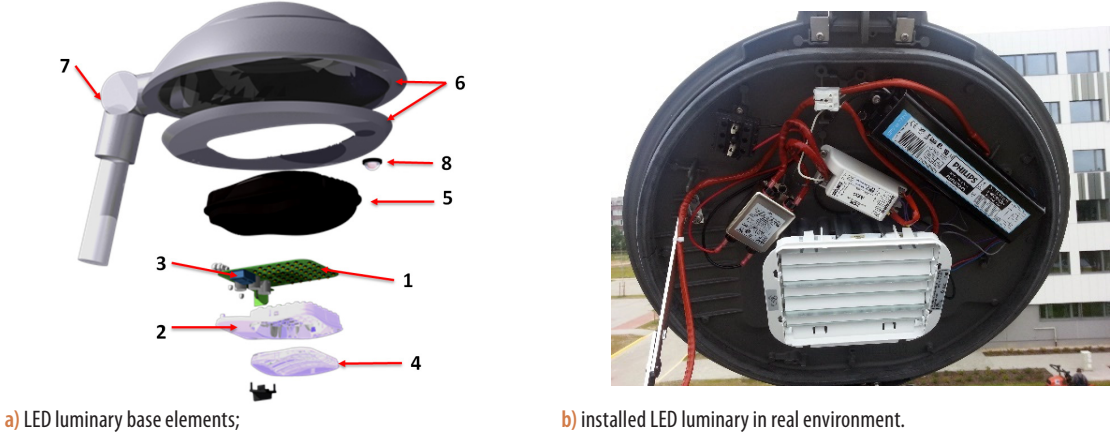


Fig. 2.1. LED luminary and main elements [15].

The casing of the luminary determines the parameters of temperature conductivity (including the service life of LED), as well as such mechanical parameters as IP class (protection against dust and humidity) and IK class (impact resistance). L70 and L90 tests help to determine the theoretical LED luminary service life. LED luminary cooling system can be passive or active (the use of ventilators causes additional power consumption). In the case of passive cooling, the parameters of temperature conductivity of aluminium or similar material have to be evaluated. Additionally, a luminary can include a temperature control node that reduces the current of LED luminary automatically, to ensure that the maximum temperature of p-n junction would not be exceeded, for example, if the external temperature is over 37 °C.

To compare street LED luminaries of different manufacturers, considering their performance, the total emitted luminous flux of a luminary (Φ_L , lm) and the power of luminary (P_L , W) have to be considered, therefore the ratio of these values is the total light output efficacy – the characteristic measure is emitted lumens vs. the consumed watt (lm/W).

$$\eta_L = \frac{\Phi_L}{P_L}, \quad (2.1)$$

$$\Phi_L = \Phi_{LED} - \Phi_1 - \Phi_2 - \Phi_3 - \Phi_4, \quad (2.2)$$

where Φ_{LED} – LED chip (light source) emitted light flow that includes losses in primary optics (according to the manufacturers of diodes, on average approximately 6 %);

Φ_1 – light losses incurred at the moment of manufacturing of luminary, when the LED chip is soldered on the PCB plate and the soldering appliance damages the primary lens of the LED chip (in case when wrong nozzle is used);

Φ_2 – light losses in the secondary optics (luminary lenses, reflectors, diffusers);

Φ_3 – light losses on the inner sides of luminary casing (up to 2 %);

Φ_4 – light losses in the protective casing of luminary (acrylic, glass, polycarbonate or borosilicate), where the losses depending on the material cause loss of 2–15 %;

$$P_L = \left(P_{LED\text{chip}} \times n_{\text{number of chips}} \right) + P_{\text{driver}} \quad (2.3)$$

The total power of a luminary (P_L , W) is determined by the sum of consumed energy of n -number of LED chips and ballast power losses that is determined by the efficiency of ballast at the respective LED chip working current.

As the light emitted by LED is proportional to its consumed current (DC), then the level of emitted light can be controlled by means of constant current regulation in every LED string, which is also the most efficient way (28). It is possible to use the power pulse width modulation (PWM), however, as LED is very sensitive towards the changes in current, it can cause blinking and stroboscopic effect.

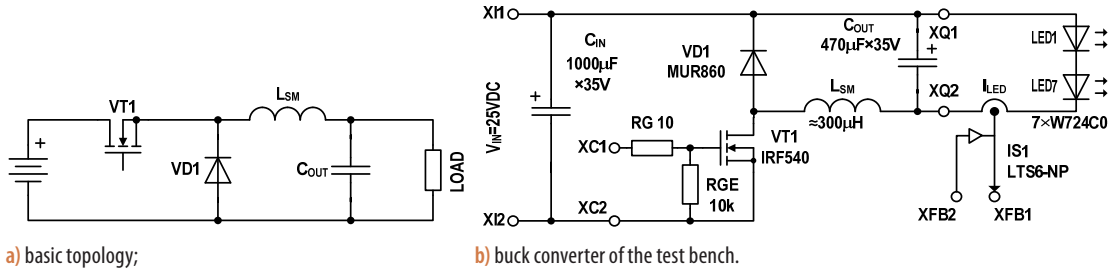


Fig. 2.2. Buck (step-down) converter in dimming application.

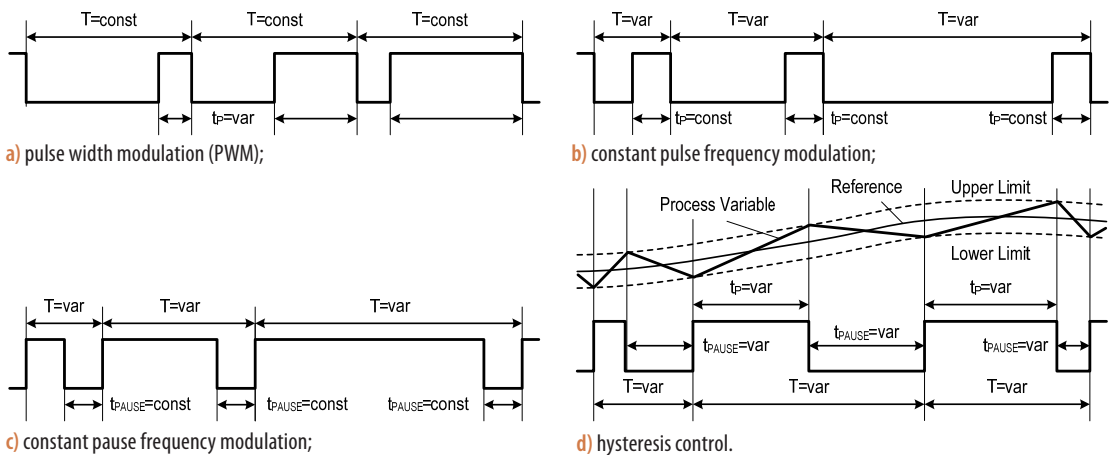


Fig. 2.3. Approaches to generation of the control signals (24).

As LED itself is a low direct voltage element, it should be powered with constant and continuous current. Therefore, DC/DC section is mainly necessary because LED luminary is powered by the alternating voltage (hereinafter - 230 V AC) line. Due to this, different direct voltage converter circuits are used as current regulators: for example, Buck, Boost, Buck-Boost, and Buck-Boost with zero pulsation (Chook) type converters. To determine the most efficient solution for generating command signals, there are several methods (see Fig. 2.3) and circuit in Fig. 2.2 b) can be used to create a testing device for light regulation.

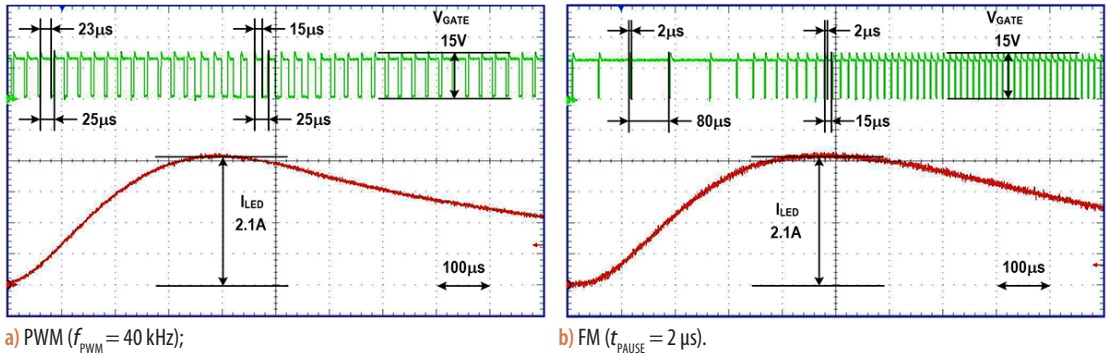


Fig. 2.4. Dynamic performance of modulation methods (developed by I. Galkins).

During experiments, incoming/outgoing voltage (U_{IN} and U_{LED}) and current (I_{IN} and I_{LED}) were determined. Then, input and output power were calculated (P_{IN} and P_{LED}). Considering the power, the efficiency coefficient of converter is calculated:

$$\eta(\%) = 100 \frac{P_{LED}}{P_{IN}} = 100 \frac{U_{LED} I_{LED}}{U_{IN} I_{IN}}. \quad (2.4)$$

The light regulator efficiency coefficient calculated using this method is shown in Fig. 2.5; in the case of PWM management, these curves look traditionally - with clear losses in the ends of the curve. The data obtained analytically and experimentally prove that the efficiency described above is high with all the verified management methods. The efficiency determined with FM (2 μs) is steadier over all the power range, moreover, with 7 % less losses at the minimum power (5 W) in dimmed mode.

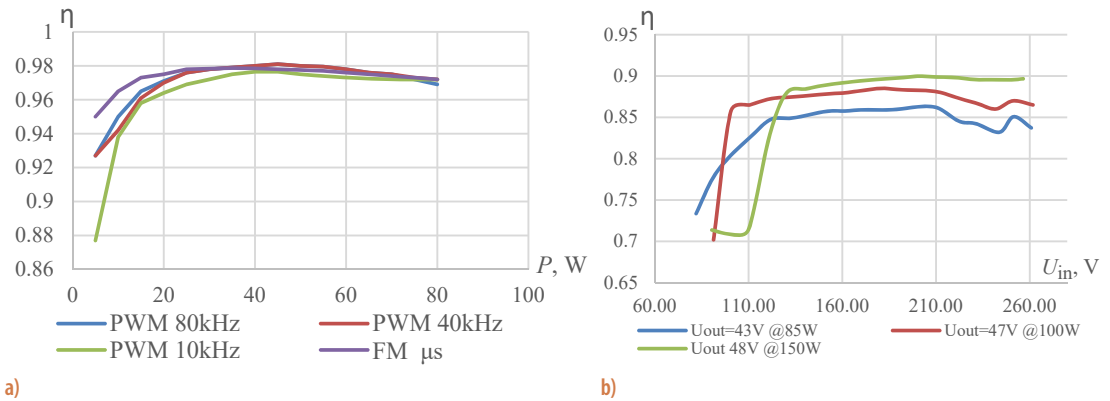


Fig. 2.5. a) – Efficiency of step-down LED dimmer; b) – resonant converter (DER212) with PFC circuit.

Luminaries often contain one or several LED strings that have to be controlled separately. The ballasts of street luminaries require rectifier and power factor corrector (PFC) for a higher input current quality. Therefore, to join smaller size, mass and expenses with equal functionality, it is advised to use one rectifier and PFC for all LED current regulators (Fig. 2.6). The actual efficiency of the AC/DC boost resonant half-bridge converter (25) (implemented on “Power Integrations” integral micro-scheme PL-C810PG standard circuit (DER212)) is provided in Fig. 2.5 b).

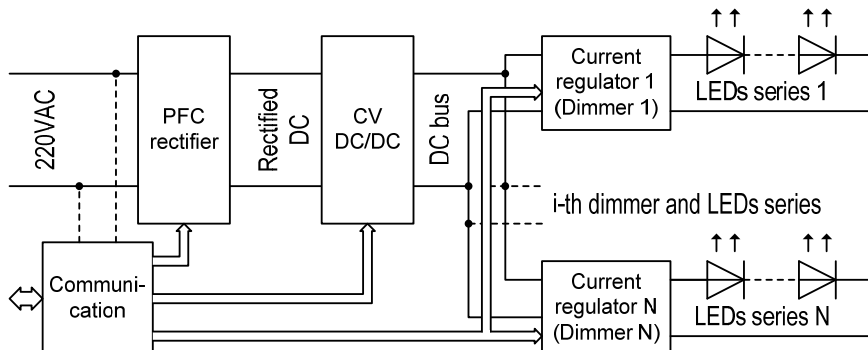


Fig. 2.6. Luminary power supply for multiple parallel LED series.

Several LED luminaries were developed within the framework of the Doctoral Thesis. **LED1 luminary** (Fig. 2.7) is constructed based on the matrix type LED (Fig. 2.8) circuit that is composed of 4 parallel strings with 14 LED diodes in each string. Diode power is 1 W (colour: warm white), therefore the planned maximum power of luminary is 56 W.

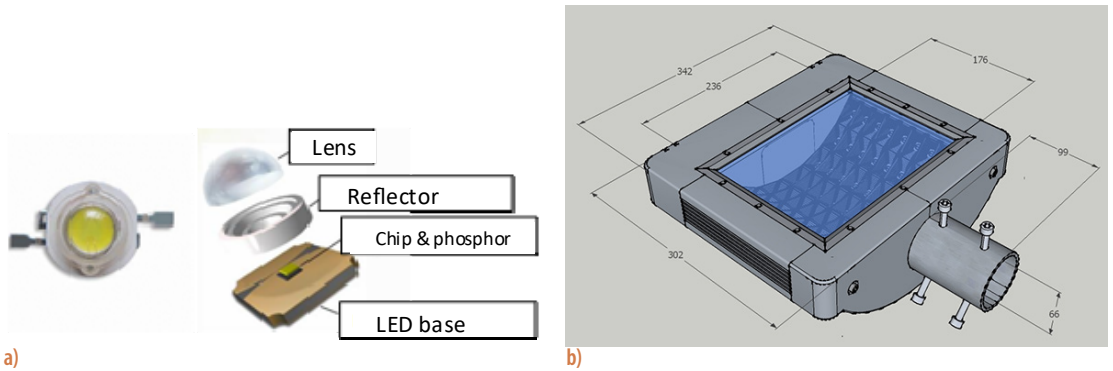


Fig. 2.7. LED luminary 1: a) light source (1 W) sample and b) LED1 luminary housing.

The main internal structural construction layout of LED luminary is shown in Fig. 2.8; and it consists of 4 key blocks.

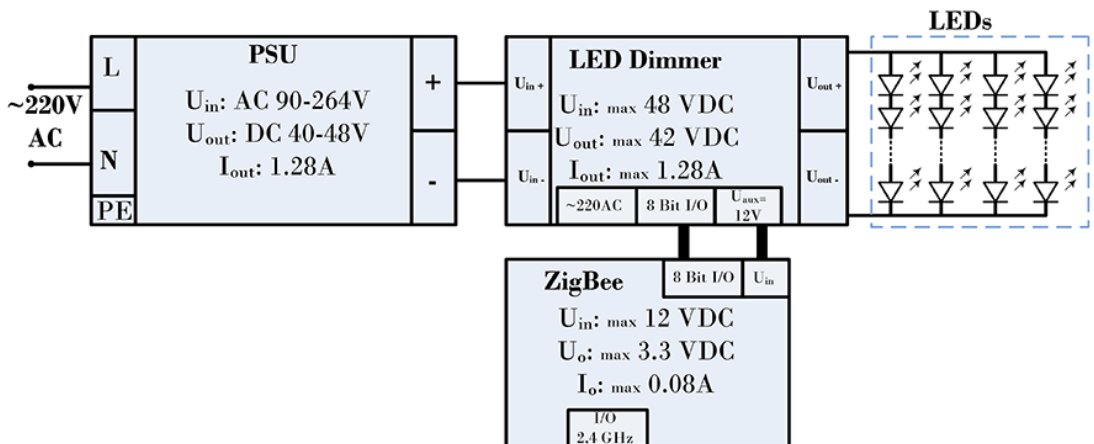
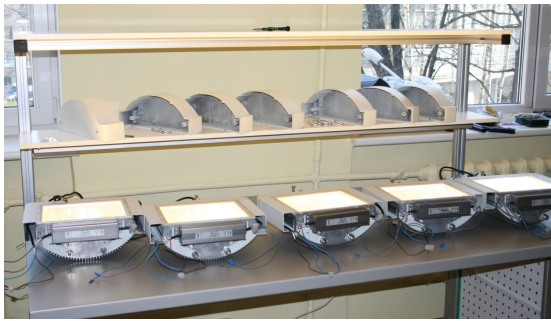


Fig. 2.8. Internal structure of the LED1 luminary.

PSU is a standard, non-regulating constant current supply block that changes 220 V alternating voltage to 40–48 V direct voltage. In this case, the experimentally determined (Fig. 2.9 a)) maximum output power is 61.5 W, and maximum constant output current is 1.28A.

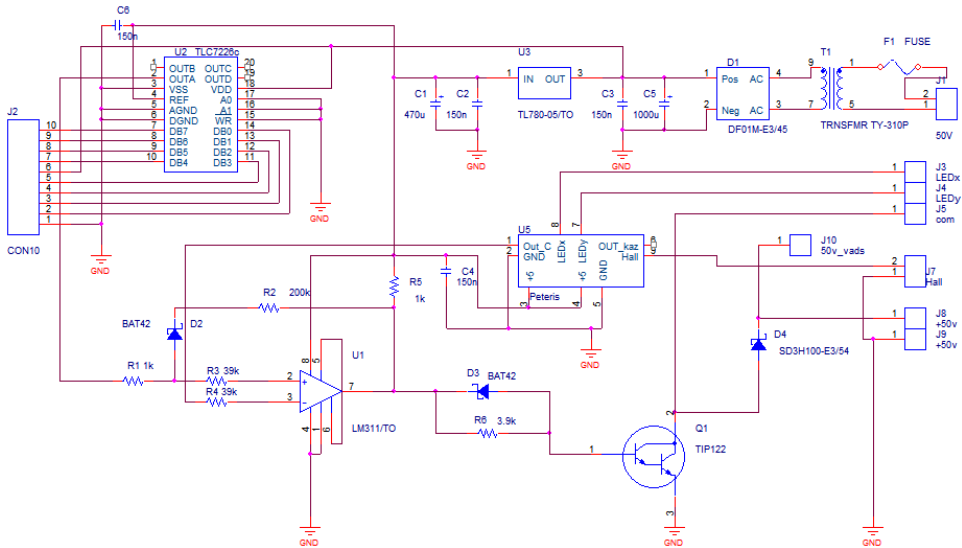


a) luminary testing stand;

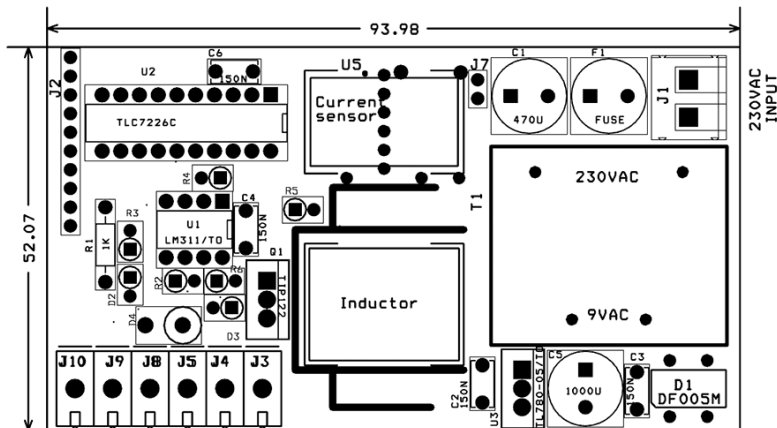


b) dimmer with integrated control module.

Fig. 2.9. Testing of LED1 luminary housing and integration of dimmer and control unit.



a) principal electrical scheme;



b) PCB plate design and electronic component placement.

Fig. 2.10. LED1 luminary current regulation (dimmer) scheme.

LED dimmer is the power circuit (Figs. 2.9 b) and 2.10) of smart luminary control unit that receives digital signal (for example, from FPGA (22)) and can regulate output power. Current is regulated in the range of 0–100 % considering the level and amount of light output that is not directly proportional to the current (it has rather exponential character).

ZigBee is a wireless communication and control unit transceiver part that detects external command signal and sends it to LED Dimmer that regulates the current provided to LED diodes.

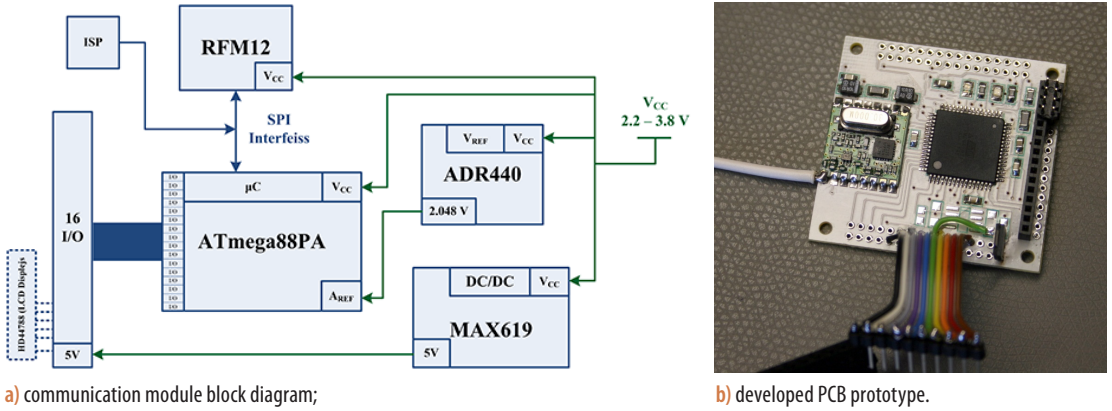


Fig. 2.11. LED1 luminary ZigBee communication module block diagram and device.

Wireless communication module (Fig. 2.11) is provided for transmission of small data packages with low data transmission speed (up to 115.2 kbps) in half-duplex mode, i.e., it cannot transmit and receive information at the same time. As the phase modulation used in the transceiver and communication synchronisation (Fig. 2.12) is performed considering the change of phase, the length of transferred data packages depends significantly from the change of data binary form “0” and “1”, i.e., changes in the carrier frequency phase by 180°. LED1 luminary testing results are displayed in Fig. 2.13, where the total efficiency at nominal power is 80 % (electrical energy maximum efficiency is 86 %) and regulating light at 40–45 W, lag in the form of hysteresis by 18 % is caused.

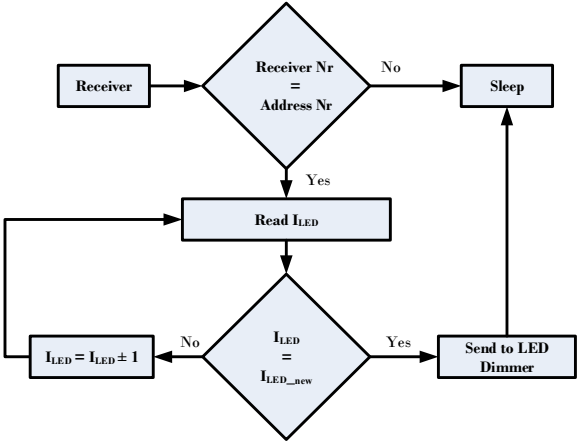


Fig. 2.12. Simplified control algorithm.

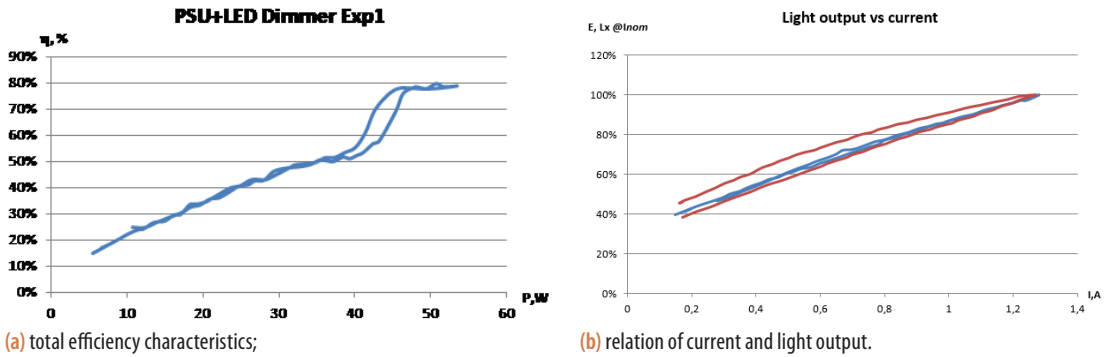


Fig. 2.13. Total efficiency characteristics (a) and relation of current and light output (b) for LED1 luminary.

LED2 luminary (power is regulated up to max. 112 W) main circuit is given in Fig. 2.14. Its operation is based on 3 LED groups each of which contains 3 parallel LED diode (Cree XPG 3 W, 4000 K) strings with 6 LED diodes in each string, every group (18 diodes) are powered by separate supply block that increases the security of operations, because if one supply block fails, the other two continue operating and street lighting will be intact and the system operator will receive a notification that the respective luminary is damaged. Damaged luminary is identified by the power measurement node whose value is changed in the digital signal and with the help of micro controller and transceiver information is transferred to the control unit and vice versa – commands are received from it. Power supply block [17] is created on the TOP204 based (SMPS) circuit for regulation of outgoing voltage with PWM, current stabilisation, micro controller management (0 – max. power, 255 – min. power) and small distance data transmission wireless communication.

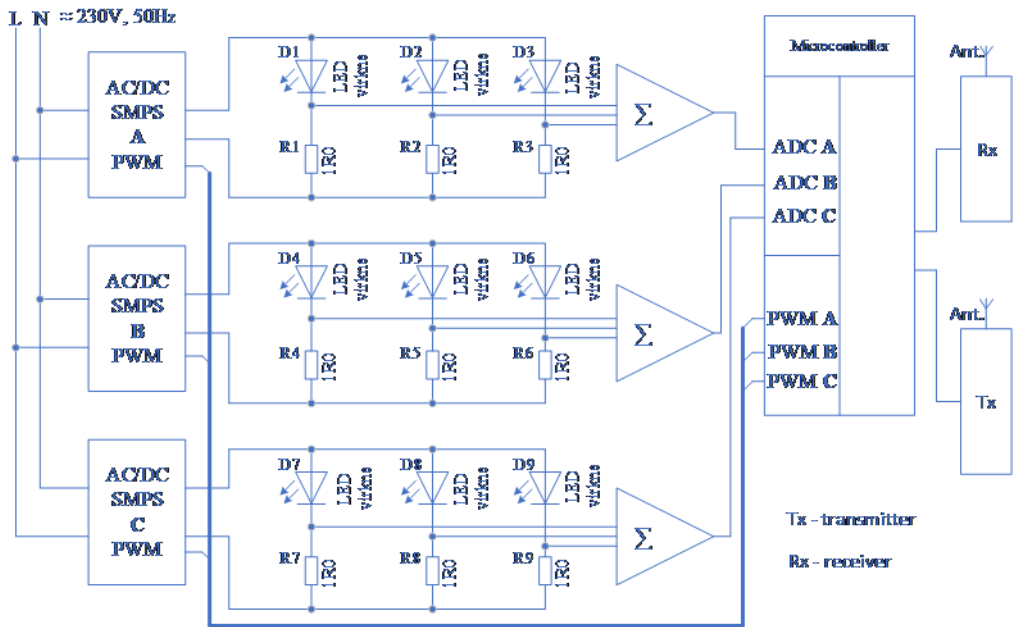
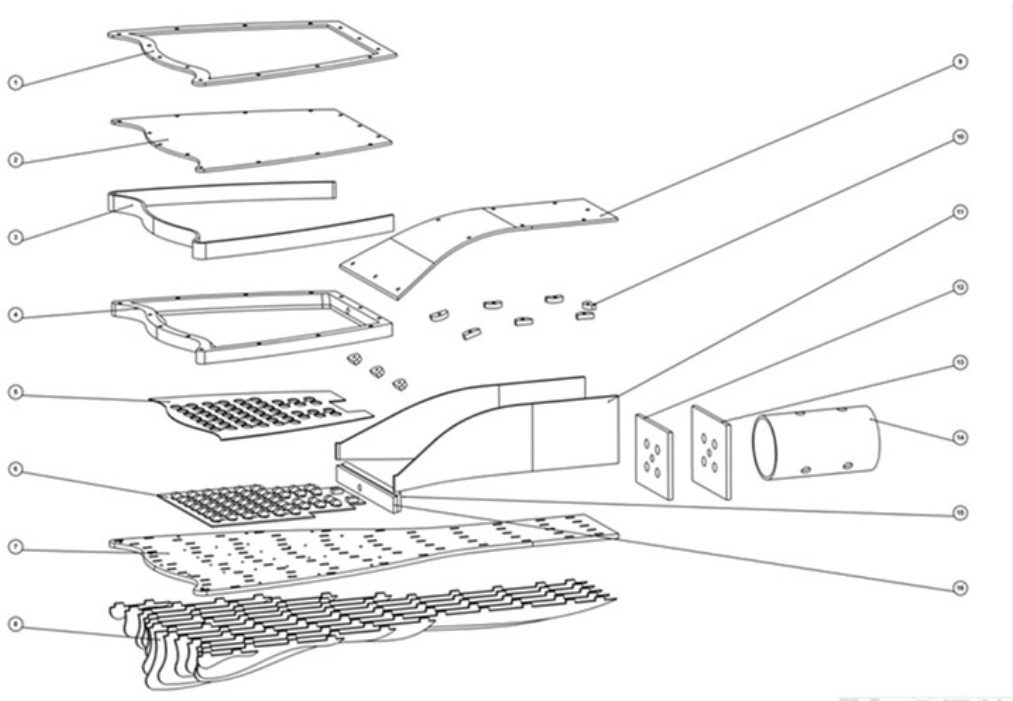


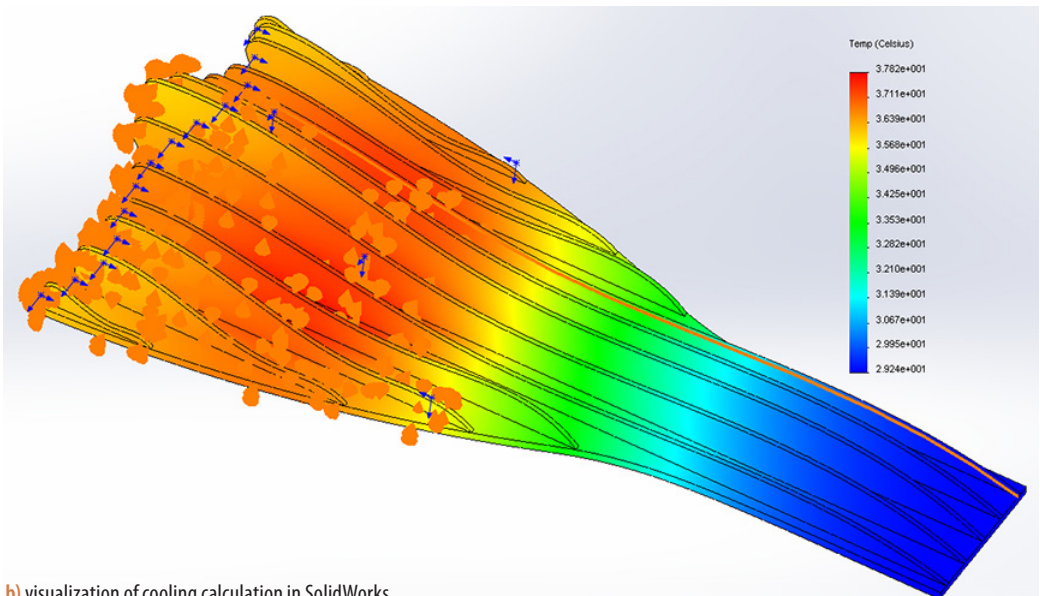
Fig. 2.14. Integration of LED2 series power supply into one luminary – functional diagram.

Figure 2.16 shows data received from wireless communication, where the efficiency of LED2 luminary is approximately 85 %. Figure 2.15 a) provides constructive/assembly solution of LED2 luminary, but Fig. 2.15 b) provides temperature change calculation results that show maximum 37 °C at 100 %

load. The developed form is unique because luminary cools down similarly in different wind directions. LED2 luminary regulating range (0–100 %) efficiency values at nominal power are given in Fig. 2.16. Figure 2.17 provides the prototype of LED2 luminary and the created aluminum PCB plate with two types of LEDIL lenses to expand the radiation of lighting that complies with the street profile and to obtain uniformity.



a) exploded view of construction;



b) visualization of cooling calculation in SolidWorks.

Fig. 2.15. LED2 luminary housing.

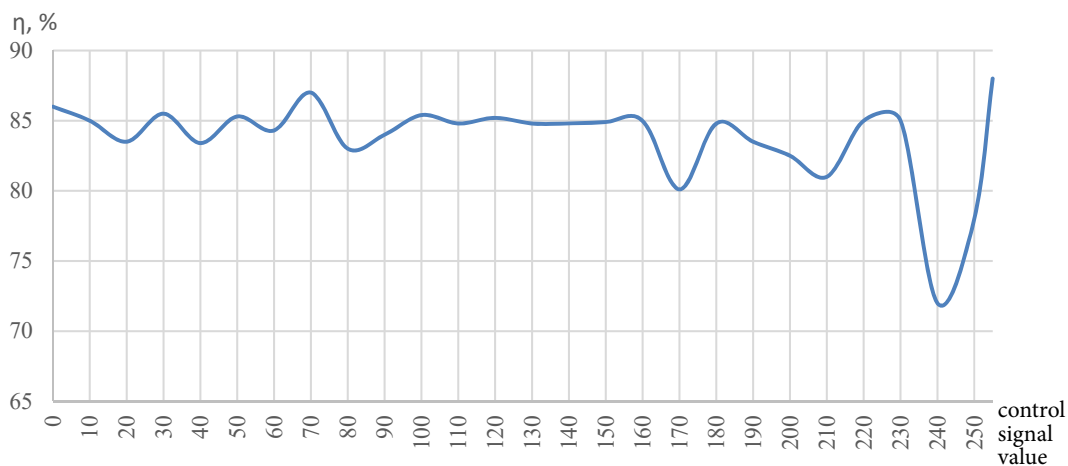
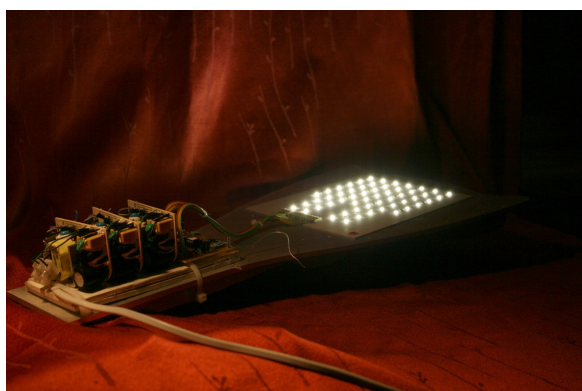
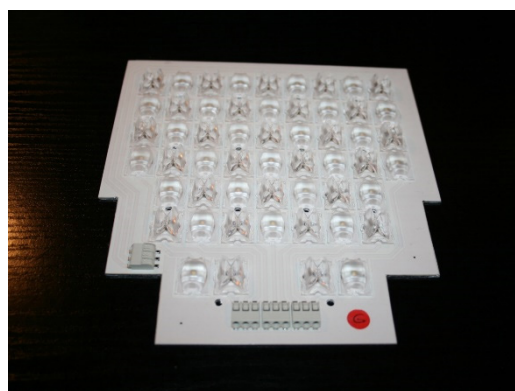


Fig. 2.16. LED2 luminary efficiency at nominal power (56 W).



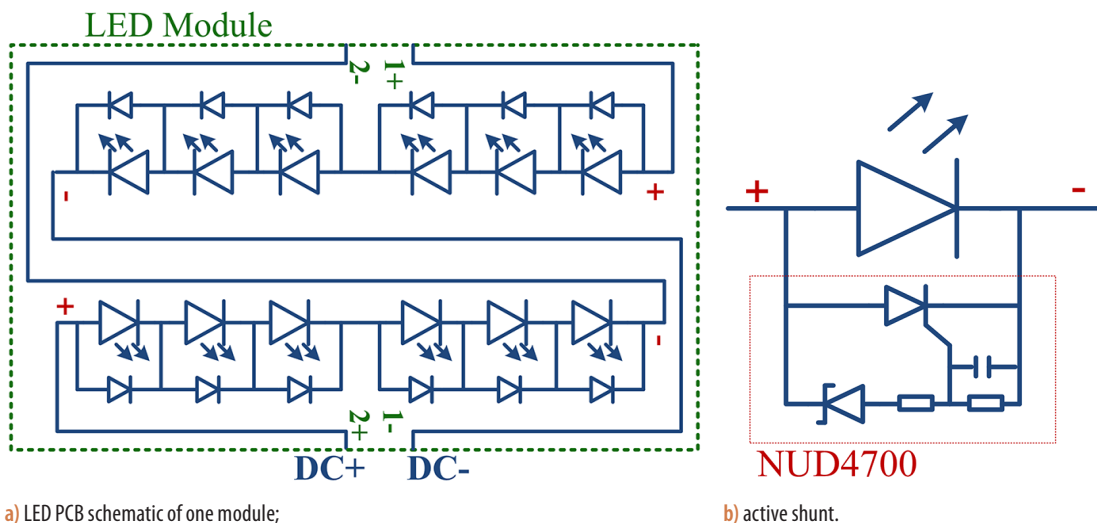
a) prototype;



b) PCB plate with two LEDIL lens types.

Fig. 2.17. LED2 luminary and its testing.

LED3 luminary was developed using the only series connection and constant current control for LED diodes. PCB module-type approach of 12 LED diodes allows to optimise manufacturing expenses and reduce the variations of types of PCB plates and rated power. PCB modules can be connected in series and parallel connection, and in the event of damage to LED diode, a parallelly connected energy efficient active shunt NUD4700 (Fig. 2.18) is provided. It is nominally provided for 1 W (350 mA at 3 V) LED diodes, however, if appropriate cooling is ensured, it can maintain current up to 1 A.



a) LED PCB schematic of one module;

b) active shunt.

Fig. 2.18. LED PCB schematic of one module (a) and active shunt (b).

Power is supplied by module LPi80CS70F20 (Fig. 2.19) with rectifier, PFC chain and DC/DC buck converter with one output, which ensures regulated constant current control for LED diodes (Fig. 2.20).

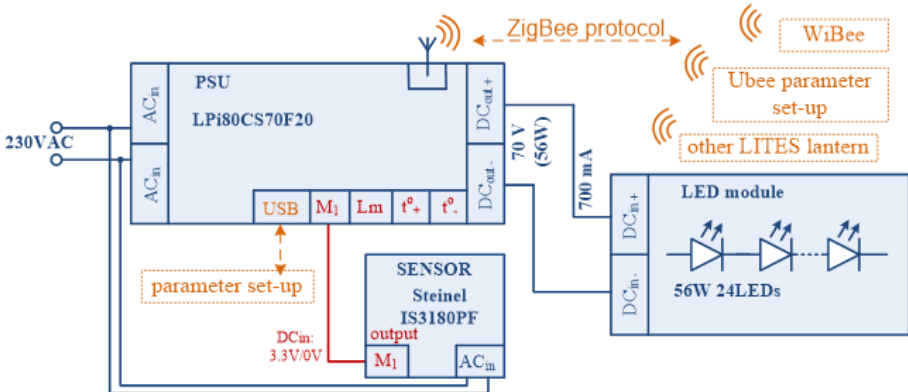


Fig. 2.19. LED3 (56 W) luminary block diagram.

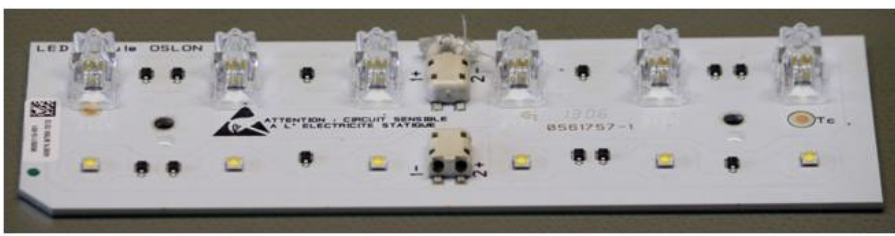


Fig. 2.20. LED3 luminary 28 W PCB plate module, voltage is 40 V_{DC} and current is 700 mA.

According to Fig. 2.21, total efficiency coefficient of LED3 56 W luminary system is 90.5 %, electromagnetic compatibility (EMC) tests of the system were conducted at the LEITC laboratory, and the tests showed compliance with regulations, as it is provided in reports in detail [15],[16].

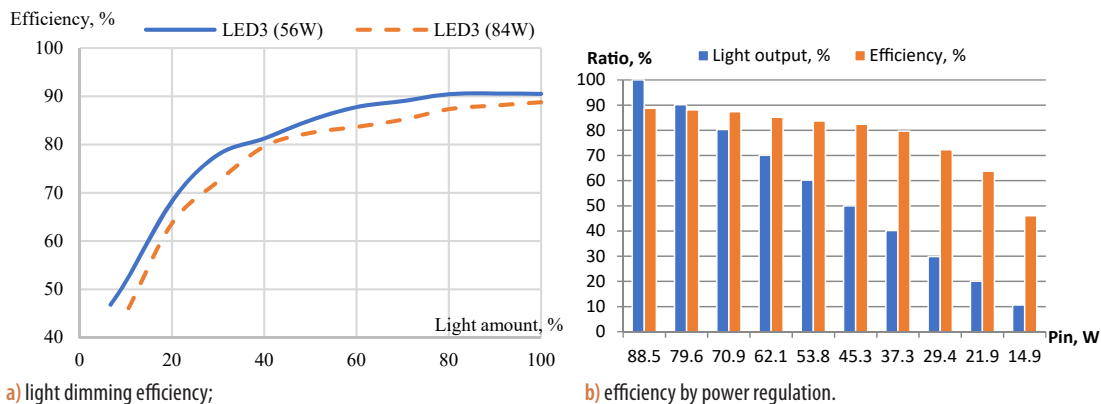


Fig. 2.21. Efficiency measurement results of full LED3 56 W luminary system.

The largest light return of LED light source in the case of matrix connection was detected with continuous current control method that emits by 19 % more light compared to pulse width modulation (PWM) and by 25 % more compared to the LED light source string on/off method.

LED light source light output is non-linear in respect to regulated output current value of power supply, and this characteristic can be used to increase the total light output of LED luminary, efficiency, colour rendering index and service life, using appropriate control methods in the LED light source driver.

Analytically and experimentally obtained data prove that the efficiency of the light regulator referred to above is high with all tested control signal techniques. Efficiency of the FM regulation method that was determined experimentally is constant in a wider range of power, but the constant pauses FM method ensures higher regulation accuracy.

The electromagnetic compatibility tests at the LEITC laboratory prove that the LED light source ballasts with the efficiency over 0.92 more often comply with regulatory requirements of electromagnetic compatibility or are closer to their threshold values compared to ballasts with lower efficiency.

Creating the smart LED light source ballast using separate electrical devices (power supply unit, driver, communication node, etc.), which individually comply with the requirements of electromagnetic compatibility but in the joint circuit (housing of luminary), does not meet the requirements due to the interaction between the emitted radio-interference. It can be prevented by installing additional electromagnetic interference filters.

In lighting control systems, for the purposes of electricity consumption accounting control signal data transmission it is possible to use different wireless communication types, using half-duplex and duplex data transmission mode. In experimental tests, it was observed that ZigBee data transmission requires stronger signal (antenna) to cover the distance of up to 100 m, however, no communication issues were observed for the standard radio signal (RxTx). Although the manufacturers of wireless communication modules and the tests of the actual transmitter-receiver prove the data transmission distance of above 500 m (and even >1 km) in a straight line, in case of more complex and larger lighting systems (long streets, the number of luminaries at least 25, many trees on the streets), the experimentally determined data transmission distance is limited to 100–120 m that covers 2–3 closest lighting poles with the average distance of 33 m. Therefore, geographical location of the segment controller (for example, ZigBee-WEB gateway) is of importance to ensure that in the star or MESH layout it would be located as much as possible in the centre, or it requires an antenna that can receive the signal better.

3. Street Lighting System Analysis

According to general and functional application, three main lighting types can be classified: indoor lighting, outdoor lighting, and decorative lighting, where each of them has more detailed types of use.

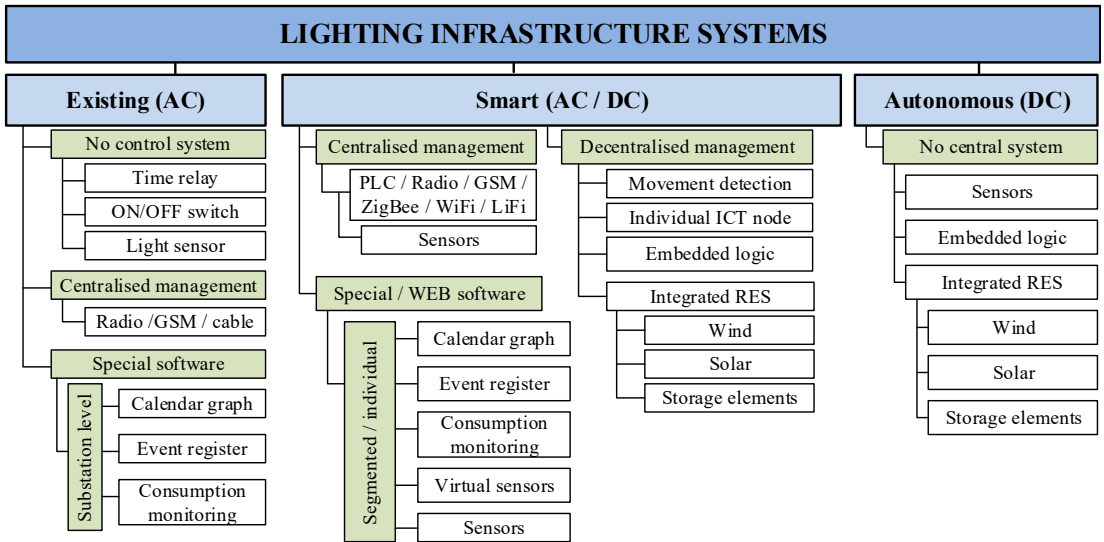


Fig. 3.1. Street lighting system classification by type of technology.

Street lighting systems can be divided in existing, smart and autonomous systems with different control options. In the course of technological development, lighting system market offers LED lighting sources that are more efficient compared to the existing ones and they allow to use new functions and features that, along with the development of information and communication technologies (ICT), allow to create lighting system classification by the technological solution (Fig. 3.1).

The smart lighting systems can be used almost in any lighting application type, because the only thing that changes is the constructive solution of lighting source, and the technological solution can be used as is. As the street lighting sector is rather energy-intensive and it is financed using public funding sources, the street lighting sector will be further analysed in this Doctoral Thesis.

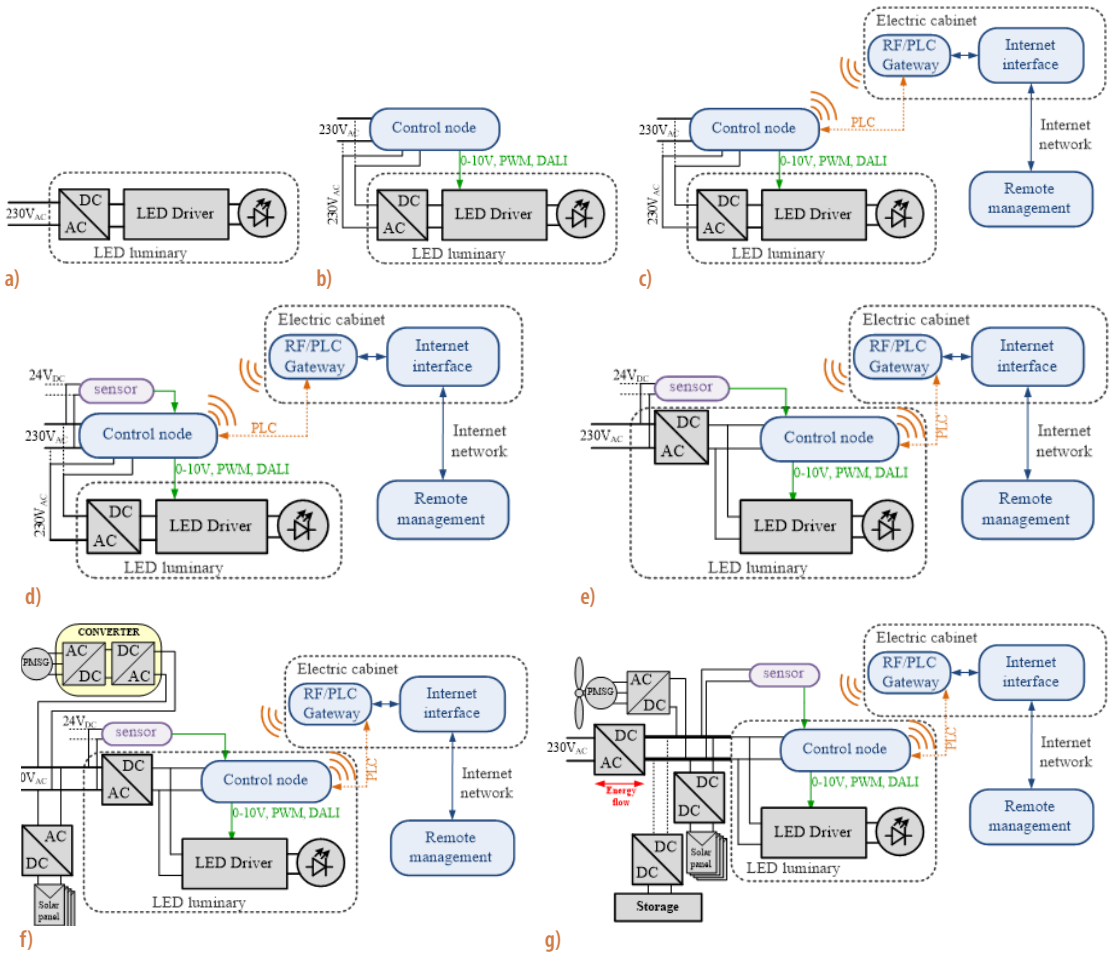


Fig. 3.2. Types of lighting system architecture.

There can be different types of lighting system architectures, as it is shown in Fig. 3.2: (a) is a simple LED luminaire circuit and connection with the existing lighting network; architecture (b) is integrating (a) with an individual luminaire calendar schedule control node, or with control node and communication network (c), and smart LED street control systems with external control node and movement sensor (d), or with a built-in control node and movement sensor (e); as well as future architecture with renewable sources connected in an AC network (f) and renewable sources connected in a DC micro-network (g). Replacing HPS luminaries with LED, the benefits of the architecture (a)–(e) can be analytically compared, as it is reflected in articles in detail (17 and 18).

Retaining similar 4,352 hour lighting per year and ME4-ME6 quality and traffic safety requirements for “Zunda krastmala” street section with 30 gb HPS (Philips Malaga SGS102 150 W) luminaries, in case of change to LED (Philips Indal BGP623) the electricity consumption decreases by 47.2 % (Type a)), and with the control node and sensor self-consumption, by 67.49 % (b), 65.67 % (c), 76.75 % (d), and 77.93 % (e), which proves that the smart control systems provide additional 30 % savings compared to simple replacement with LED (18). To determine savings of movement or “context-type” (13) sensors, the night time intervals provided in Fig. 3.3 and traffic intensity data of SJSC Latvian State Roads were used, as well as electricity consumption over the period of E_{12} applying Formula (3.1).

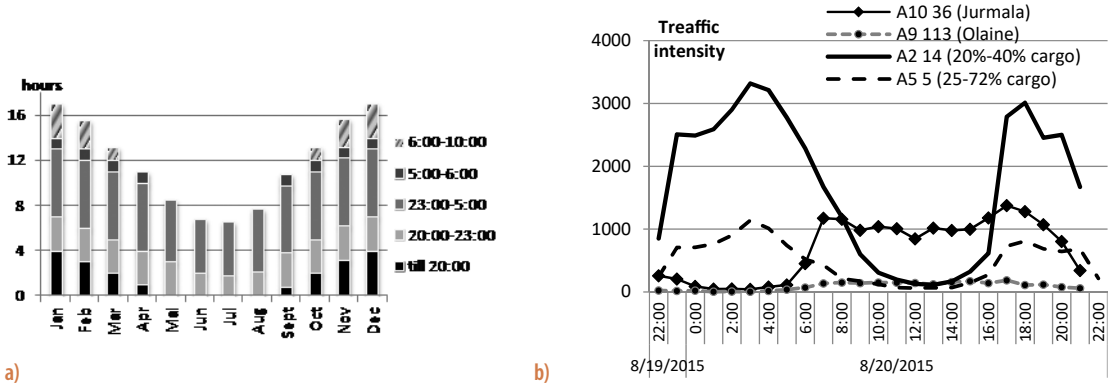


Fig. 3.3. Hour distribution of night zones (a) and LVC traffic intensity data (b).

$$E_{I2} = P_{\min} \times (t_1 + t_2) + \frac{(P_{\max} - P_{\min}) \times (t_1 + t_2)}{2} + P_{\max} \times t_{ON}, \quad (3.1)$$

where P_{\min} is the lowest set power level of luminary;
 P_{\max} is maximum set power level in the specific night period;
 t_1 is set time from the moment when sensor starts operating until reaching P_{\max} ;
 t_2 is set dimming time (from P_{\max} to the moment of reaching P_{\min});
 t_{ON} is the period when luminary operates in P_{\max} mode.

One of the key tasks of smart lighting system is to perform accounting and monitoring of each individual LED luminary in real time, and, with the help of ICT, transfer the data to WEB server. It means that every luminary requires electricity consumption device that can measure voltage and current, therefore determining the momentary active power values (Fig. 3.4 b) and calculating full and reactive values. Different measuring methods can be used, but one of the solutions (patented by the author) is provided in Fig. 3.4 a).

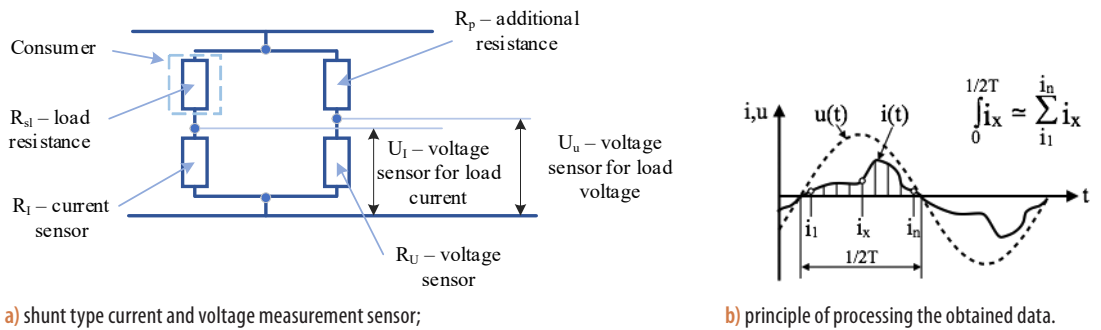


Fig. 3.4. Consumption current and voltage measurement [13],[14].

Figure 3.5 provides measurement data example for one-week experimental power measurements (for the case of P_{\max}) for three 400 W sodium luminaries (P1) and three LED luminaries (P3) with equivalent emitted light flux; supplied voltage and surrounding parameters were the same in both cases. It can be observed that the power consumed by sodium luminaries varies over one day and week, where changes are in the range of 12.5 %, but in case of LED, the consumption is steady and similar over the period of all week. To have accurate data in the smart lighting management system, real measured power values have to be used instead of the analytically calculated (assuming that the consumed power is constant over time).

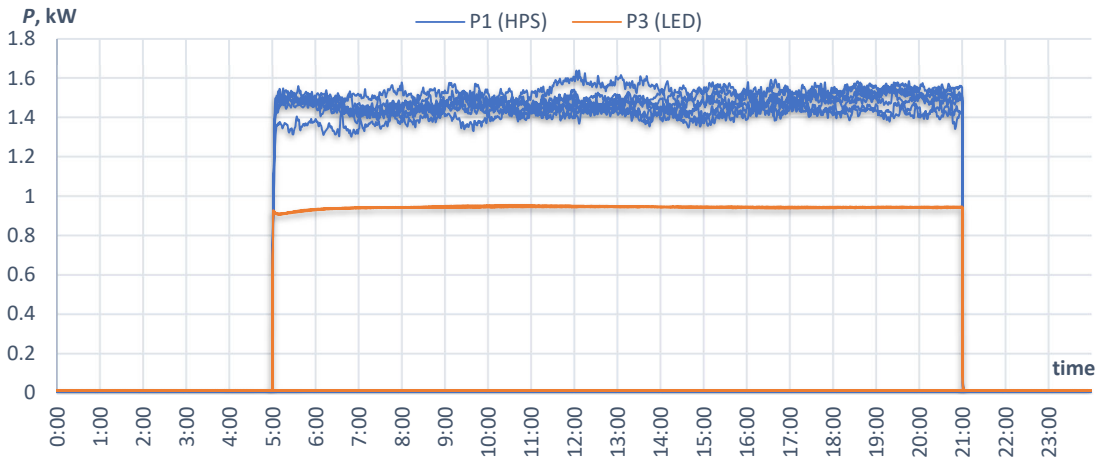


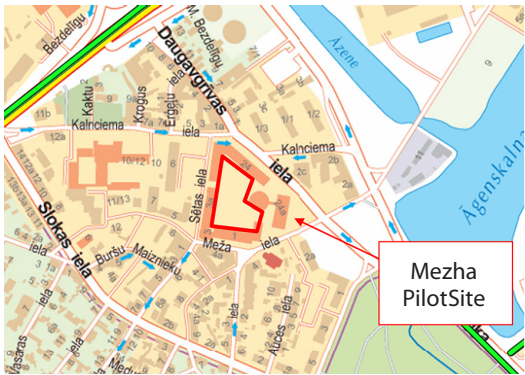
Fig. 3.5. Eksperimentally obtained data.

To determine electricity consumption of LED luminaries, Hall type sensors with clear hysteresis loop show different (dual) measurement resulting values in case of increase and decrease of current, therefore, such a solution is not accurate. After testing several industrially manufactured electricity meters (9), their measurements at different network voltage values showed 0.1 % error with two exceptions, where it reaches 0.7 %. In case of different network frequencies, measurement error increases up to 0.5 % on average, with some exceptions (at 65 Hz) up to 1.15 %. Light poles might be connected to AC network at night and to DC micro-grid during the day-time using renewable energy resources and electric vehicle or electric scooter charging opportunities, therefore, it will be a necessity for dynamic and two-way electricity accounting (9), similarly as in the case of industrial DC micro networks (11).

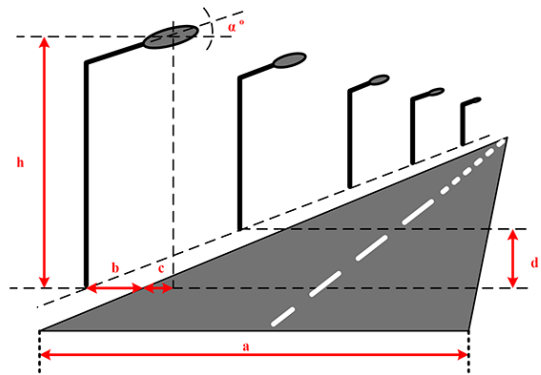
The created thermally compensated shunt can measure energy consumption in both directions (receives or returns to the network) (15), moreover, for both sinusoidal and non-sinusoidal signals, with different impulse widths (12), where, compared to industrial shunt-type power analyser Newtons N4L PPA5530, the developed option was on average by 08–3.22 % more accurate and at low power values – even by 21.6 % more accurate (12). This allows to integrate the node that detects the electricity consumption of LED luminaries in PCB plate itself, thereby reducing manufacturing expenses compared to offered solutions that use more expensive material with low resistance temperature coefficient. The novelty of the solution is proved by the received WIPO patent (28).

4. Experimental Tests of the Developed New Lighting System And Analysis of Obtained Results

In total 7 pcs of LED1 luminaries were installed in Riga on Meža Street lighting line that is located in the inner yard of Riga Technical University (Fig. 4.1). As the selected line was built earlier, measurements might be impacted by the condition of the old cables, therefore, overhead line was installed and the old poles were re-equipped. The line is long enough for the measurements to be close to average typical lighting line of parks, parking lots and similar squares in Riga. Street/square type profile applicable standards, geometric and lighting class parameters are given in Table 4.1.



a) LED luminary installation at Meža Street;



b) street profile.

Fig. 41. Testing at RTU – Meža Street Pilot-Site.

Table 4.1

Street/area type profile parameters and other data

Meža Street average profile parameters:			Other parameters:
$a =$	4 / 30	m	Lighting situation description D1 (from CIE 140)
$b =$	0.7	m	Existing lighting class: S4
$c =$	1.3	m	Testing class: S4
$d =$	15 / 20	m	Maintenance coefficient: 0.67 (approx.)
$h =$	8.5	m	Existing luminary: Philips Malaga with high pressure sodium vapour lamp SON-T (150 W and 70 W). Accordingly retrofitted with LED1 and LED2 type luminaries
$\alpha =$	15	°	
lanes:	1	pc	
Street tarmac:	Porous asphalt		

According to long-term measurements, the system, without dimming mode (only replacement of luminaries), saved on average 40 % electricity, comparing to the consumption by sodium high pressure luminaries, and using calendar dimming mode it can save up to 60 %. In the case of LED2 luminaries, testing was conducted in Meža Street and Zunda Krastmala using a previously set calendar schedule for the day (Fig. 4.2). As a result, after 22 sodium luminaries (2604 W consumption) were replaced with LED (1628 W), savings without dimming were 37 %, but with dimming mode 49 % (in winter) and 83 % (in summer) that is related to the duration of night hours, in total saving 56 % on average.

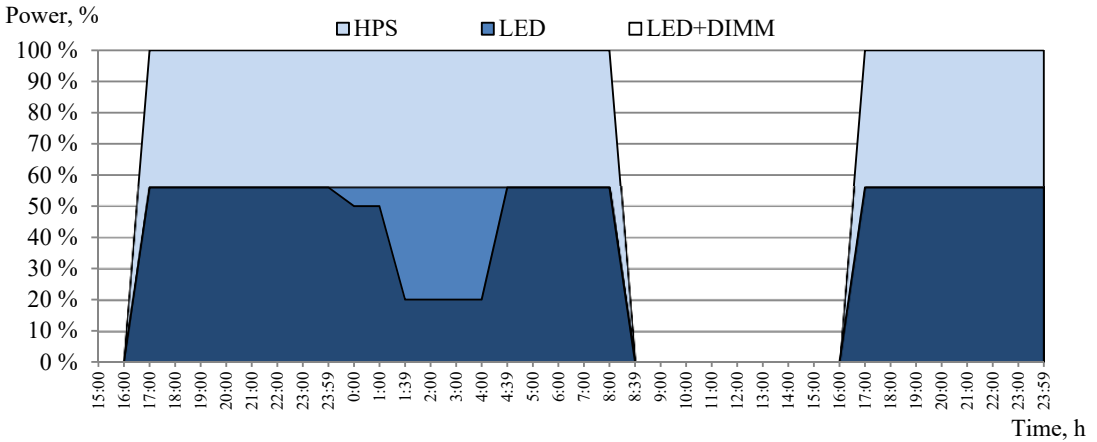


Fig. 4.2. Applied ON/OFF dimming profiles during daytime.

Smart lighting system with movement sensors was developed (Fig. 4.3), and in total 29 LED3 luminaries were installed at ipsala campus, 11 luminaries (95 W) on Zunda Krastmala and 18 luminaries (65 W) on Azenes Street. Electrical connection circuit of luminaries is provided in Fig. 4.4, and energy meters were installed in the metal poles (Fig. 4.4.c) in order to compare with the data from the smart control system. To detect movement and control luminaries, Steinel IS3180PF and Bosch DS720i TriTech® sensors (Fig. 4.5) were used, and in 2020 the radar-type detecting sensor was added that is able to determine also the traffic movement direction and approximate speed (Figs. 4.6 and 4.7).

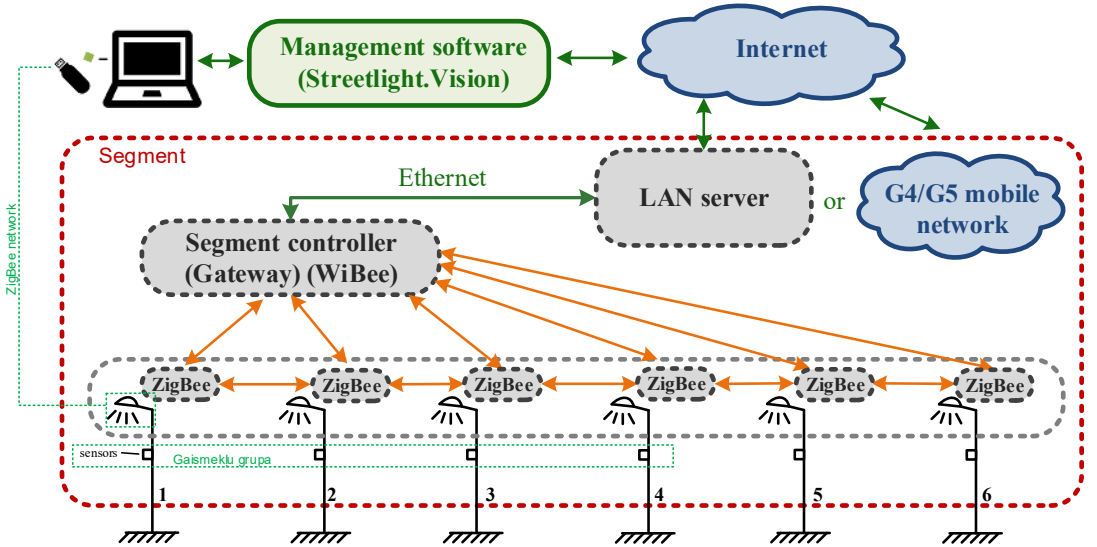


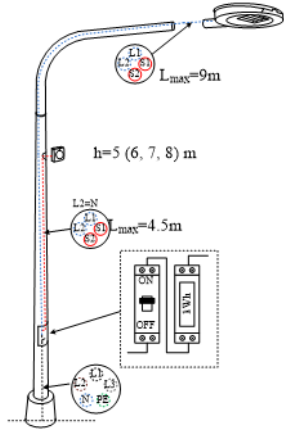
Fig. 4.3. Structural diagram of created smart lighting system.

For the radar (Doppler effect) sensor (2 and 8) complex Fourier transformation (FFT) was applied, where the measured speed is proportionate to the Doppler deviation frequency f_{doppler} , in line with Formulas (4.1) and (4.2).

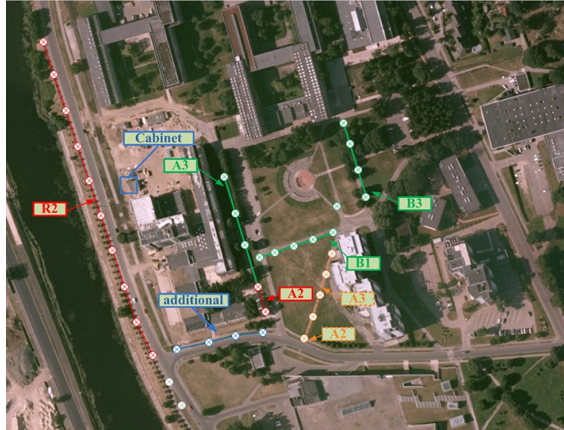
$$f_{\text{doppler}} = \text{bin} \times \frac{f_{\text{sample}}}{N_{\text{FFT}}} = \text{bin} \times \frac{f_{\text{sample}}}{256}, \quad (4.1)$$

$$v = \frac{bin \times f_{sample}}{256 \times 44,7 \times \cos \alpha} \quad (4.2)$$

where bin - FFT is output value that is proportional to Doppler frequency;
 f_{sample} - FFT measurements/resolution frequency;
 N_{FFT} - FFT width in bits;
 v - speed value, km/h.



a) metallic (zinc) pole;



b) LED luminaire placement;



c) ABB C11 110-300.

Fig. 4.4. LED luminaire placement and electrical wiring at Kipsala Pilot Site.



a) Steinel IS3180PF;



b) Bosch DS720i TriTech®;



c) microwave radar sensor.

Fig. 4.5. Kipsala Pilot Site used movement detection sensors.

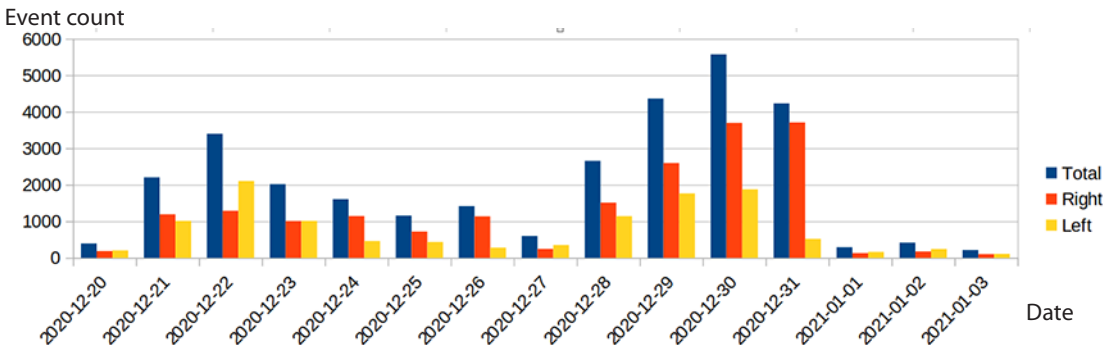


Fig. 4.6. Measurement sample of developed radar sensor movement direction.

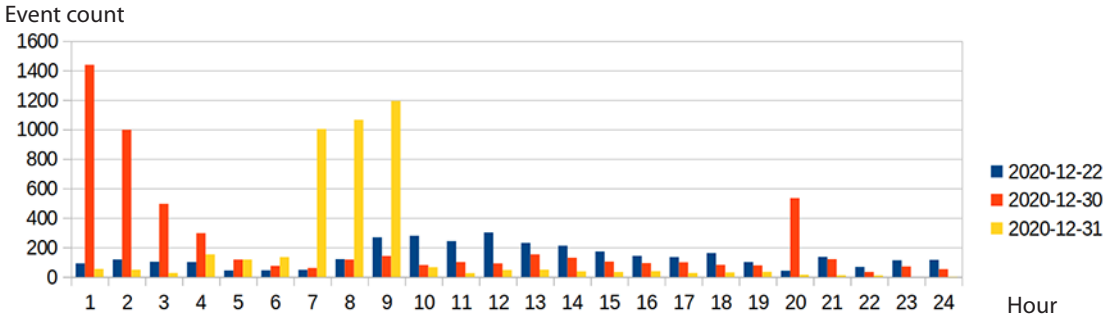


Fig. 4.7. Measurement sample of developed radar sensor traffic intensity.

At the Kipsala Pilot Site, Philips SGS high pressure sodium luminaries with total power of 3450 W (18 light bulbs (100 W) and 11 (150 W) light bulbs) were replaced with 29 smart LED luminaries Thorn Dyana (71.22 Lm/W, 4000 K), installed power of 2094 W that provide by 40 % less installed power and by 20 % better average lighting (E_{AV} , lx) and by 34 % better lighting homogeneity (U_L), ($L_{av} = 0.52 \text{ cd}^{-1}\text{m}^2$ and $U_0 = 0.62$). Lighting pollution U_{FR} (4.3) is the ratio of direct upward light flow (U_{DLF}) to upward light flow reflected from the road surface (U_{RLF}).

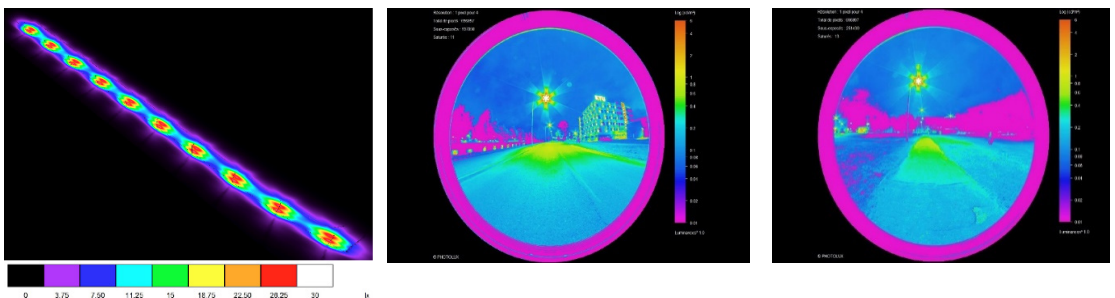
$$U_{FR} = \frac{U_{DLF}}{U_{RLF}} \tag{4.3}$$

If U_{FR} value is below 10, it is considered a very good result, if $U_{FR} < 1$, it is an excellent result. After Dialux 4.0 modelling (see Fig. 4.8 a)) and practical measurements (see Fig. 4.8 b, c)), in case of Philips SGS luminaries $U_{FR} = 3.0$ and in case of Thorn Dyana LED luminaries with full power $U_{FR} = 2.75$, and $U_{FR} = 1.0$ at 20 % dimmed mode.

Table 4.2

Dialux modelling and real power/illumination measurement results in different regimes

Illumination / measurement points	E (80 %), lx			E (60 %), lx			E (40 %), lx			E (20 %), lx		
	M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
$E_{(lx)}$ (measured in 2020)	25	7	24	20	6	20	14	4	14	8	3	8
Measured in 2014	28	10.7	17	-	-	-	-	-	-	7.1	3	7
Dialux simulation in 2014	20	8.19	20	10	4.49	10	6.24	2.92	6.24	3.12	1.35	3.12
Deviation, %	+19	-17	+17	+50	+21	+49	+56	+33	+56	+61	+49	+59



a) Dialux simulation (150 W HPS); b) 95 W LED measurements at full power; c) at 20 % power.

Fig. 4.8. Kipsala Pilot Site: a) Dialux simulation; b) 95 W LED measurements at full power; and c) at 20 % power.

The Dialux model was compared with real measurements obtained over several years, conducting $E(lx)$ measurements (Table 4.2) in the middle of the street, M1 and M3 are points perpendicular to the lighting pole, and M2 is the point between M1 and M3 poles. Comparing simulations of LED luminaries conducted in 2014 (at MF of 1.00) and measurements taken in 2020, it can be concluded that there is more light than necessary according to the standard, and the power can be reduced (dimming value increased), thereby obtaining additional savings. As smart lighting was installed before, to determine savings caused by the replaced luminaries, analytical calculation approach can be applied if the calendar schedule of city lighting is known, or by calculating the length of night (T_d , hours) of a specific day of the year (n), using the sun movement vector [18] with declination angle (δ) and degree of latitude of the specific location (φ) with Formula (4.4).

$$T_d = 24 - \frac{2}{15} \left(\arccos \left(\min \left(\max \left(-\tan(\varphi) \tan(\delta), -1 \right), 1 \right) \right) \right), \tag{4.4}$$

where $\delta = 23,45 \times \sin \left(\frac{360}{365} (284 + n) \right)$.

Based on calculations, it can be concluded that reduction of electricity consumption in the case of LED2 luminary would be 38 %, but in the case of smart LED luminaries it is 42 %, according to the consumption division by months (Fig. 4.9).

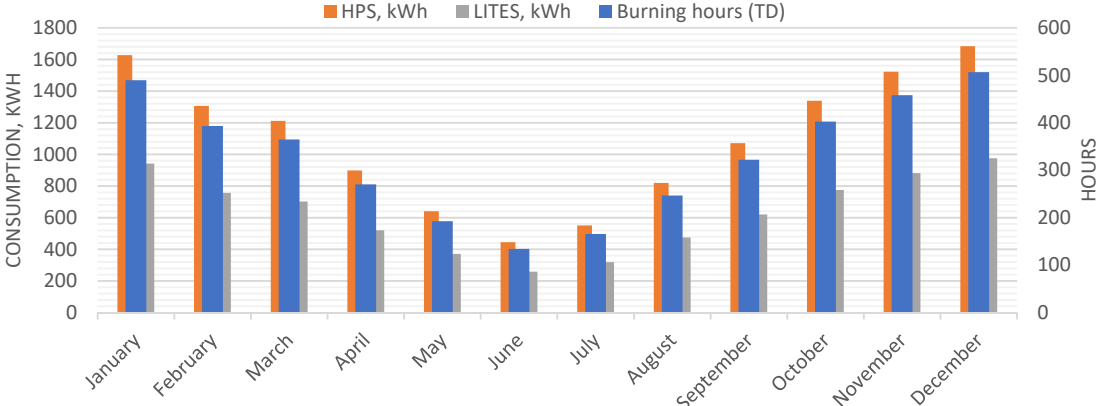


Fig. 4.9. Analytically calculated electrical energy consumption for high pressure vapour (HPS) and smart LED luminary cases.

Based on the data provided by installed electricity meters (Fig. 4.10) that were read twice per month in the respective period, it can be concluded that 4 LED luminaries (01–04) consume more electricity compared to others, which is related to the fact that luminary LITES95_01 is installed at the crossing and its sensor turns on the next 3 luminaries, therefore causing additional 88–108 kWh (18 %) consumption. Therefore, it can be concluded that movement sensors or statistical data algorithm is required that can identify traffic movement direction at the crossing, which would consequently reduce the consumption when traffic moves in another direction.

Consumption, kWh

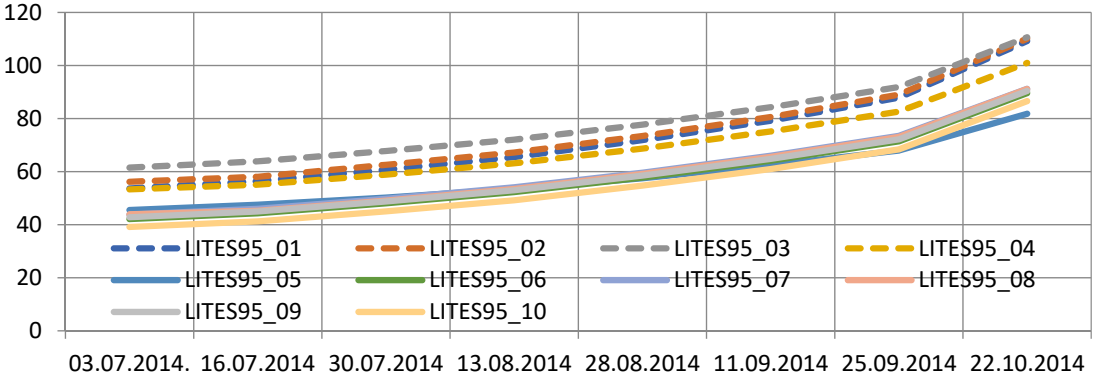


Fig. 4.10. Cumulative electrical energy readings (kWh) for each lighting pole.

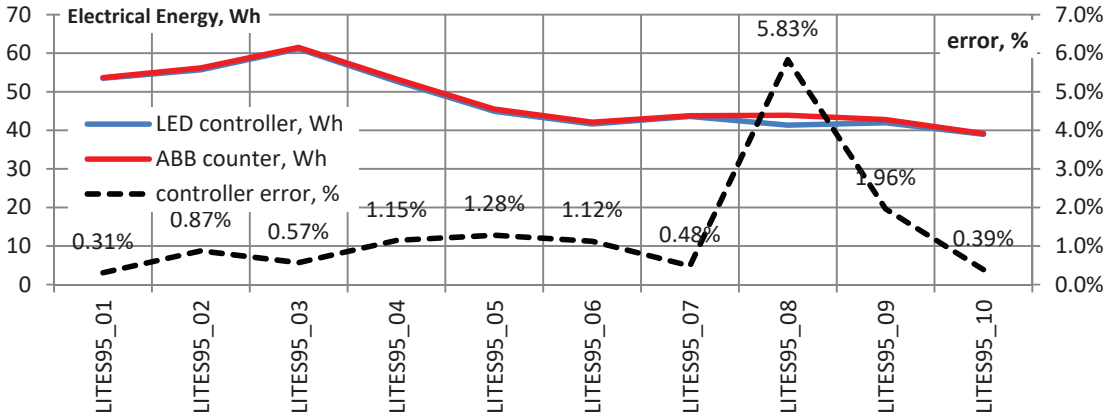


Fig. 4.11. Comparison of 95 W luminary (# 1–10) controller and energy meter readings.

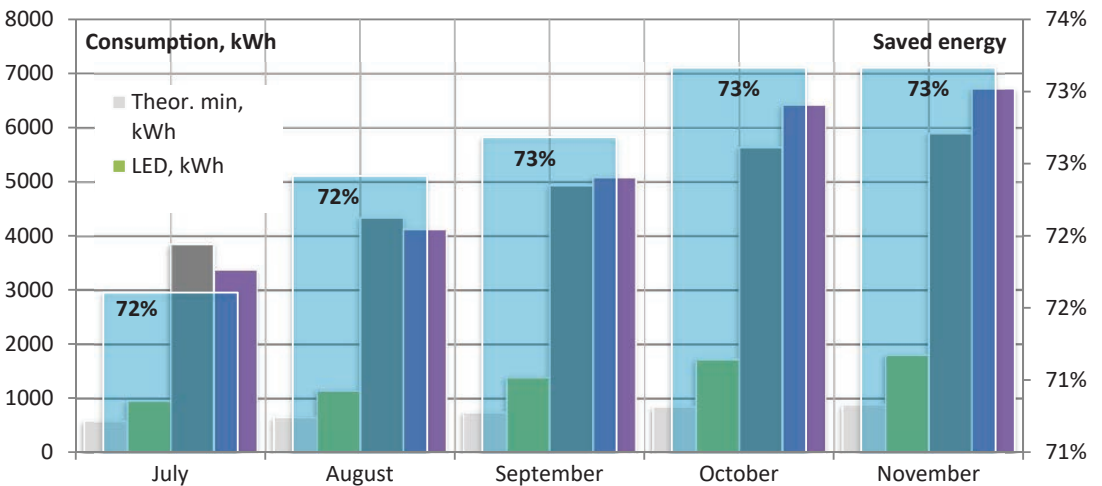


Fig. 4.12. Real energy consumption of smart lighting system at Kırsala Pilot Site.

Comparing the data sent by the LED luminary controllers to the segment controller (Fig. 3.2 e)), which sends data to WEB control software with the installed electricity meter readings (Fig. 4.11), it can be concluded that the deviation is 0.31–5.83 %, which in this case provides average error of 1.4 % that is a good result for the LED luminary power measurement node.

The lighting system of smart luminaries (LED3 type) with the movement sensor regulating mode reduces electricity consumption by 73 %, compared to the previously installed sodium luminaries over several months (Fig. 4.12). To understand street load against traffic intensity, the minimum consumption was analytically calculated: when no traffic intensity exists and LED luminary is dimmed to the minimum level, and maximum consumption was calculated: when luminary operates in maximum power mode, in line with the programmed luminary regulating profile (maximum traffic intensity for the respective hour of the day). It can be concluded that during the dark months of the year, energy efficiency and safety can be improved (the amount of lighting) if traffic intensity data for specific hours is known, which would consequently allow to apply the street M class (according to LVS 13210 standard).

The smart lighting system Citintely installed in Daugavpils was analysed as an independent system (it is similar to the smart system installed in Ķīpsala (Fig. 4.3)) that uses radio (RxTx) signal communication, and to detect movement – a radar (*Doppler effect*) type sensors are used. System with 1346 LED luminaries was installed in three city areas with different traffic intensity, on 65 different streets, out of which 33 streets were in the centre (M3/M4/M5 class) and others were M4/M5 and M5/M6 class streets in the suburbs. The goal of the measurements of power, lux, candle and spectral content was to determine the compliance of lighting system quality with the Dialux calculations (standard LVS CEN/TR 13201-1:2015) for M class, as well as to assess the dimming modes of LED luminaries in real life (1).

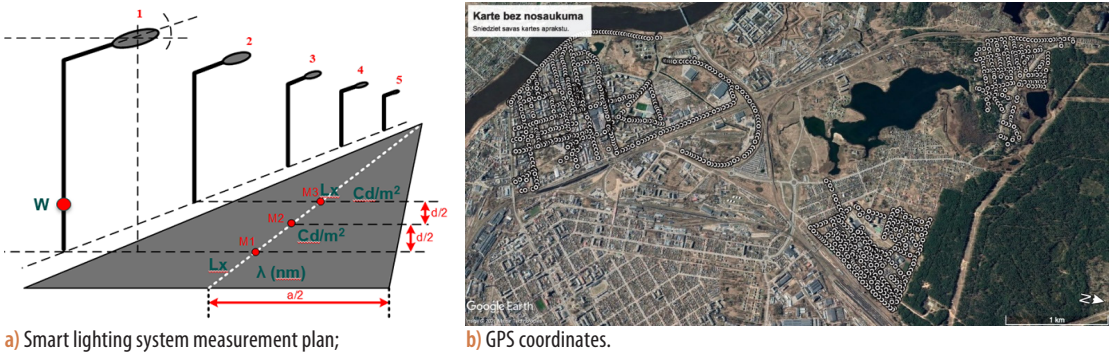


Fig. 4.13. Smart lighting system measurement plan (a) and suburban GPS coordinates (b).

Light spectrum of each LED luminary was measured (AvaSpec-2048-USB2-UA (200–1200 nm)) and E_{spot} (luxmeter Hagner EC1) under the luminary in the middle of the street (Fig. 4.13), and for each rated power type of LED luminaries (37–137 W) power (Rohde & Schwarz RTH1004) value, street lighting and reflected illuminance from the road surface (candles – Konica Minolta LS-110) measurements (in total 130) were conducted.

Based on the measurement data, it can be concluded that in almost all cases, the actual lighting in the measurement spot on the street is higher than needed according to the Dialux model to comply with the minimum requirements for the specific ME class (Fig. 4.14). Exceptions were observed only on the streets with dense tree leafage or incorrectly placed lighting consoles. Based on the obtained values, it can be concluded that the actual amount of lighting is on average by 63 % higher than necessary, which can serve as energy saving potential. Such a deviation can be partially explained by the fact that in the Dialux calculations maintenance coefficient (MF) was used with the value 0.8–0.85, average street width and average distance between lamp poles not always comply with the actual situation.

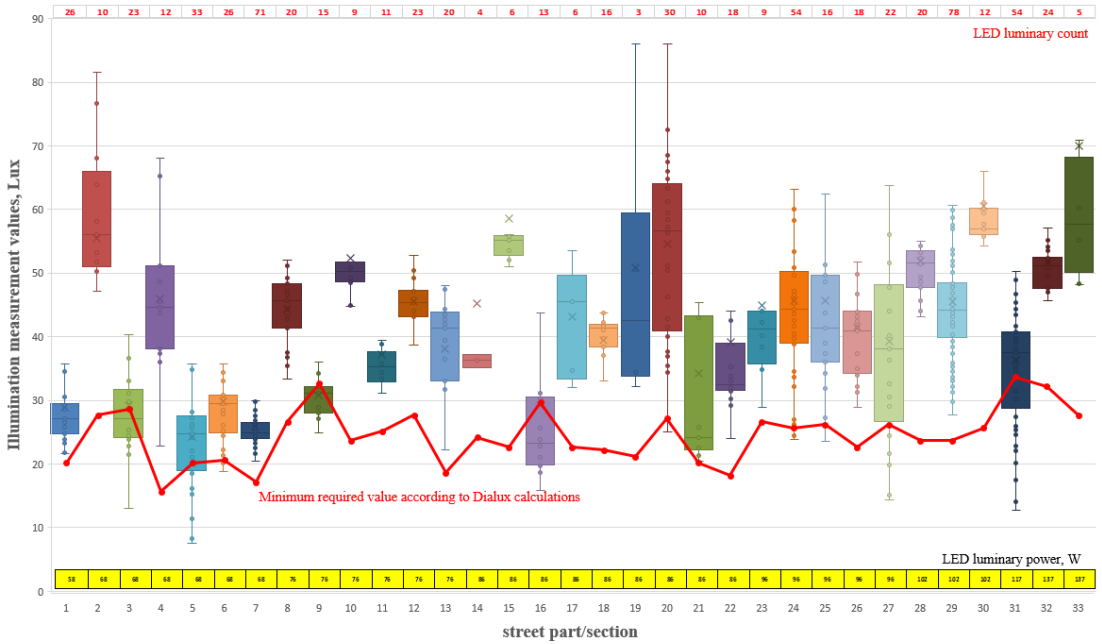


Fig. 4.14. Comparison of measured and Dialux calculation values.

As it is a smart system that is regulated based on the movement sensor and previously set dimming profile, it is interesting to view the total actual energy consumption of the devices installed in the lamp post in working conditions. In the Dialux calculations, linearised (proportional light and power) reduction approach was used to determine compliance with the respective ME class for the specific street.

According to Fig. 4.14, it can be concluded that the actual power reduction is not linearly proportional to percentage reduction, therefore non-linear approach has been applied, which is characteristic for LED diodes vs. light output. In the graph, differences between the planned installed power (P_{nom}) and actually measured ($P_{measured}$) power can be viewed, which are related to changes in the installation progress without introducing changes in the work plans (project). As opposed to the dimmed modes, at 100 % power, it can be concluded that LED luminary consumes on average by 6.7 % more than the nominally defined, which proves that the regulating method has to be improved, including also self-consumption of control and sensor devices, which would comply with the concept of smart luminary and the end user could count on realistic total consumption value.

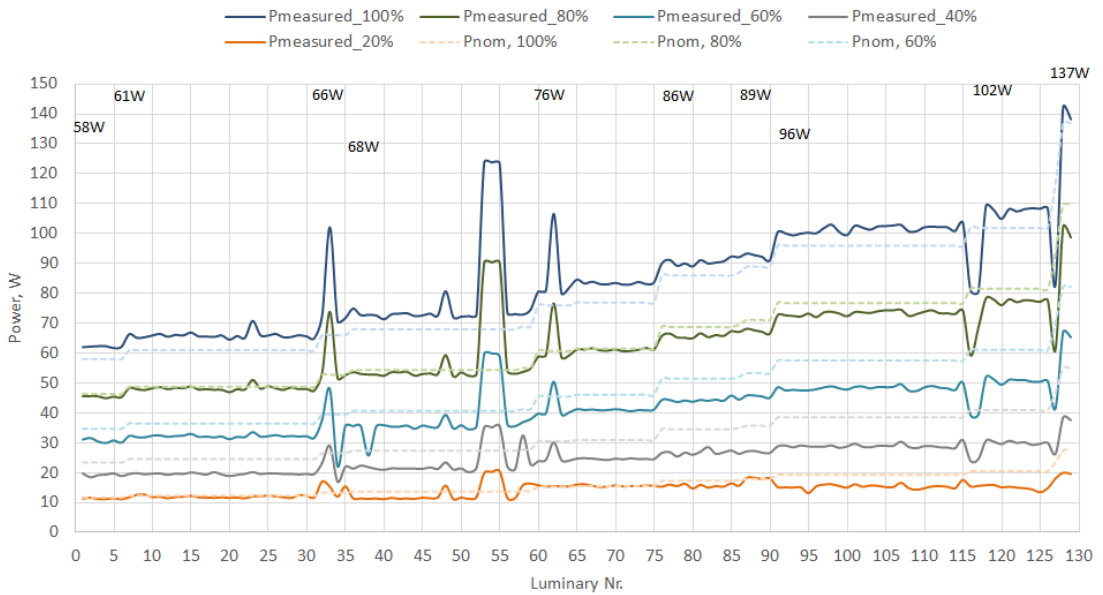


Fig. 4.15. Measured LED luminary (130 pcs) power values in dimming regime.

Smart street lighting systems, equipped with LED luminaries and movement sensors, can reduce electricity consumption by 69–73 %, and at the same time reduce the power of the installed luminaries by more than 50 %, ensuring the same or improved lighting quality parameters, if compared to the existing sodium high pressure light bulbs.

In case of smart LED lighting systems without movement sensors, it would allow to save approximately 51–72 % of electricity per month, which is up to 60 % on average per year, and the power of installed luminaries could be reduced by approximately 40 %, ensuring also lighting quality that complies with the norms and regulations.

Practical lighting measurements of new LED lighting systems show that the amount of actual lighting is on average by 63 % more than necessary, which consequently can be a potential electrical energy savings. Such a deviation can be partially explained by the fact that in the Dialux calculations maintenance coefficient (MF) was used with the value 0.8–0.85, average street width and average distance between lighting poles not always comply with the actual situation. As a result of measurements of the smart lighting systems, it is comparatively easy to change the almost linear light return (lx) and power (W) coherence, ensuring appropriate lighting class (M) for each lighting pole.

5. Adaptive Control Algorithm for Lighting System Led Luminaries

“Lighting upon demand” [19] or traffic-adaptive [22], [23] lighting management systems remain a topical issue. According to the LVS standards [10] it is already allowed to create 4 time zones (Δt_n) during night, defining their M or C classes, increasing or decreasing the lighting and P_{max}/P_{min} power levels respectively. If PIR (2 and 4), radar (7) or other dynamic movement detection sensors are used (1), the number of zones can be higher - every hour of night time can be a separate zone. The existing lighting management systems already can provide more than four of such time zones (Fig. 5.1). In this case t_0 is 3:00 p.m.; $t_1 = 5:00$ p.m.; $t_2 = 10:00$ p.m.; $t_3 = 00:00$ p.m.; $t_4 = 5:00$ a.m.; $t_5 = 7:00$ a.m.; and $t_6 = 9:00$ a.m.

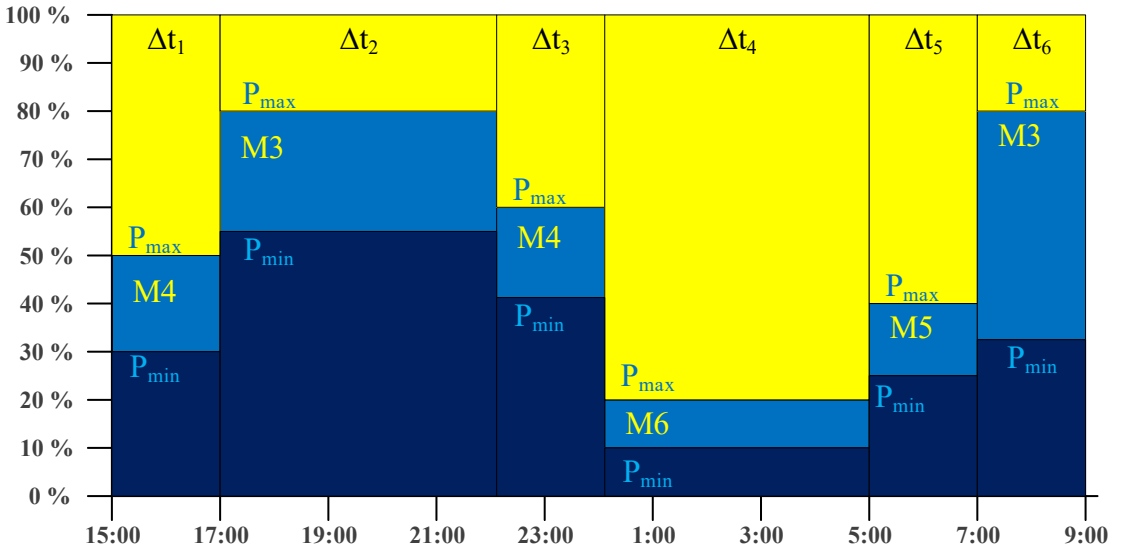


Fig. 5.1. Time slots of LED luminary dimming regimes and M class application sample.

Standard 13201-1 [10] provides road lighting of M class and C class conflict zone selection principles, considering geometric and traffic data. Standard 13201-2, in turn, provides minimum requirements for each class, where key quality parameters are average lighting (L , $cd \cdot m^{-2}$), regularity of horizontal lighting (U_0), irregularity of longitudinality (U_1), dazzling coefficient (f_{TI}) and background lighting (R_{EI}), and for C class average horizontal lighting (E , lx) and regularity (U_0).

Table 5.1

Minimal illumination average values for C and M class

M class	M1	M2	M3	M4	M5	M6
$L, cd \cdot m^{-2}$	2	1.5	1	0.75	0.5	0.3
C class	C0	C1	C2	C3	C4	C5
E, lx	40	30	20	15	10	7.5

Comparatively, the lux values of C class are higher than M class, but to go from the candle units to approximate lux units, a linear coherency can be used (5.1). In the management software, such approach would allow to simplify the E_{spot} lighting value obtained in Dialux programme and actually measured, therefore allowing to determine more accurate required power to comply with the requirements of lighting class (5).

$$E(lx) = 1.027 \times (M)^2 - 13.7 \times (M) + 52. \quad (5.1)$$

The lighting Class M (or C) is determined by applying Fformula (5.2), where the varying weighted sum (VWS) is used or individual parameters that create the sum are analysed, where dynamically varying parameters (Table 5.2) are traffic speed (V_v) and traffic intensity (V_i), and the constant parameters are the content of traffic participants (V_c), density of crossings (V_s), presence of parked vehicle (V_p), surrounding lighting (V_a), and complexity of navigation (V_n), considering that it is night time. The sum of constant parameters can vary between the whole value range from +8 to -1. If the VWS sum is less than 0, value “0” is used for calculations, if $M \leq 0$, Class M1 is applied.

$$M = 6 - VWS, \quad (5.2)$$

$$M = 6 - (V_v + V_i + V_c + V_s + V_j + V_n + V_a + V_n). \quad (5.3)$$

Table 5.2

Dynamic parameter (V_v) and (V_i) weight value conditions

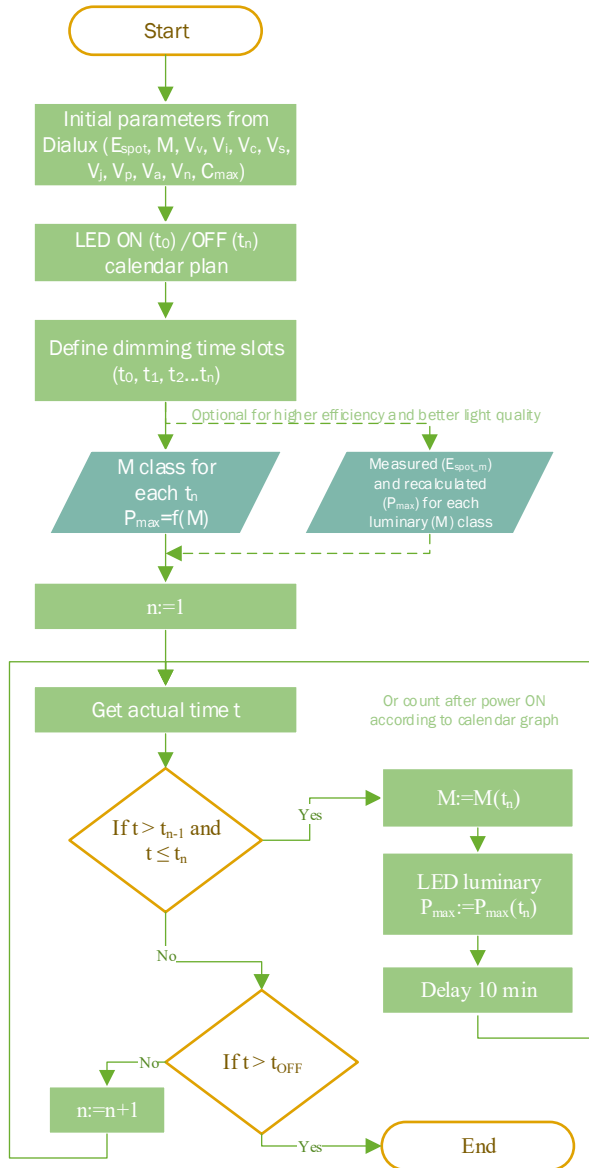
Parameter	Condition	Weight value, VW
Traffic speed (V_v)	$v \geq 100$ km/h	2
	$70 < v < 100$ km/h	1
	$70 < v < 100$ km/h	-1
	$v \leq 40$ km/h	-2
Traffic intensity (V_i) for roads with less than two lanes	>65 % of maximum capacity*	1
	35-65 % of maximum capacity	0
	<35 % of maximum capacity	-1
Traffic intensity (V_i) for roads with more than two lanes	>45 % of maximum capacity	1
	15-45 % of maximum capacity	0
	<15 % of maximum capacity	-1

* maximum capacity is maximum car count that passes road or lanes in given conditions and time slot in both directions, expressed as cars per hour or day.

LED luminary management algorithm for the option without movement sensor is provided in Fig. 5.2, where the luminary can operate independently or in case the controller has a communication node, receives management command from the central management system (segment controller). Controller memory stores initial parameter values (E_{spot} , M , V_v , V_i , V_c , V_s , V_j , V_p , V_a , V_n , C_{max}), defines the calendar lighting schedule for every day or by applying Formula 4.4, as well as sets the number and duration of dimming time zones.

From the Dialux model, M class of each zone is determined and the initial value of P_{max} power that provides it.

To ensure energy efficiency and improve lighting quality, after installation of luminaries it is possible to conduct lighting (E_{spot}) measurements (Fig. 4.13 a)) once in five years, afterwards correcting the initially set values. Further on, the actual time is determined based on the management system, built-in integral circuit or time-counting based on the city calendar schedule, according to which the time zone of the respective time of the day is determined and the appropriate M class is selected, based on which the controller regulates the LED ballast at the necessary power level. Afterwards, the actual time and actual time zone is checked every 10 minutes. If $t > t_n$, it is also checked whether it has not exceeded the turning off time when the luminary is turned off, otherwise variable n is increased by 1 and the cycle repeats in the next time zone.



5.2.att. LED luminary control algorithm for scenario without sensor data (standalone regime).

Figure 5.4 shows LED luminaries with dynamically adaptive management algorithm for the option with movement sensor data for local and network connected mode, where one sensor can manage also the nearby luminaries. Similarly to the independent mode algorithm, the beginning is identical, but as smart PIR sensor detects the traffic movement speed (V_v), traffic intensity (V_i) and maximum traffic capacity (C_{max}), traffic direction (N_L - left; N_R - right) and the number of each direction movement event or number of vehicles N over the respective time frame T (in this case it is one hour), these parameters are used for calculations. N_i is an "i" measurement in succession over a specific time period (in this case one hour), regardless of the movement direction, i.e., $N_i = N_L + N_R$.

$$V_i = N = \sum_T^{T+1} (N_i) \quad (5.4)$$

C_{\max} is expressed as the number of vehicles per day, and maximum value can be the maximum value of the previous day or maximum value over the period of several days (for example, a month). It is assumed that the maximum value of traffic capacity can increase unexpectedly only due to extraordinary circumstances or due to planned events (exhibitions, concerts, etc.), and to avoid seasonal impact on the changes of class values, shorter period is better.

$$C_{\max} = \sum_{T-24}^T (N) \tag{5.5}$$

Traffic intensity (V_i) is the actual number of vehicles at one spot, i.e., near the lighting pole.

Traffic speed (V_v), according to the standard, is the maximum speed limit that is determined by a road sign for a specific street section (or time of the day) because the actual speed data have not been obtained so far. Therefore, this parameter can be dynamically changed based on the actual values that can be obtained from the movement sensor (for more detailed construction and operating principles see publications (2 and 4). Average speed based on sensor data can be calculated in two ways:

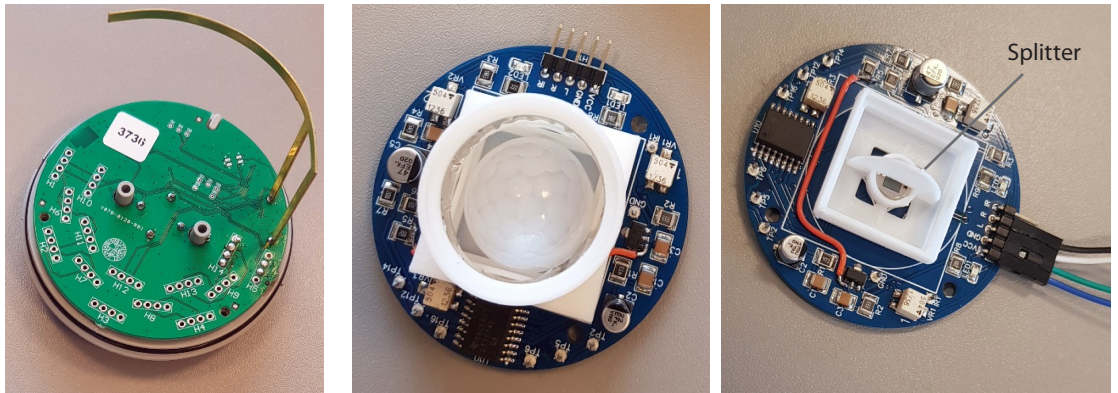
$$\bar{v} = \frac{\Delta x}{\Delta t}, \tag{5.6}$$

$$v_i = v_{\text{avg}} = \frac{d}{\Delta t}. \tag{5.7}$$

where \bar{v} is the average speed for the movement over a specific period of time $\Delta t = t_{\text{end}} - t_{\text{beginning}}$ that complies with the radar sensor approach when there are several measurements while the vehicle is in the sensor visibility zone.

v_{avg} , in turn, complies with the PIR sensor approach whose visibility zone is at 19° angle and, depending on the height of the installed sensors, the road width “ d ” in the sensor visibility zone changes and it is $d/2$ for the specific element. As the PIR sensor (Fig. 5.3 b)) has two detecting elements that are separated by a “barrier” (Fig. 5.3 c)), one of the elements detects $t_{\text{beginning}}$ and the second t_{end} ; it should be noted that in the event of movement direction change, the times are registered as opposite calculating Δt_{LR} or Δt_{RL} . As the speed can be inconsistent over entire section of the street, the speed value can be calculated as average value for entire street section, based on the total distance between lamp posts and total time spent, however, it is more difficult to identify and make calculations with such an approach for every vehicle, considering the peculiarities of the used sensor. M class requires average V_v values are calculated once in an hour ($t = 0$ up to $t = 60$ min) or once in a minute ($t = 0$ up to $t = 60$ sec), depending on the needs of dynamic algorithm accuracy.

$$V_v = \frac{\sum_{t=0}^{t=60} v_i}{i} \tag{5.8}$$



a) communication module in ZHAGA housing; b) PIR sensor PCB plate; c) splitter.

Fig. 5.3. Developed PIR sensor prototype.

For a more dynamic or more predictable lighting class change, sensor data can be calculated over a shorter period of time, for example, every 10 minutes, thereby improving the accuracy of the selected M class or creating a coefficient system, based on historical data that would predict potential increase or decrease of the M class in the coming hour.

Further on the algorithm checks in which range V_v is, consequently changing M class (M), and determines the impact of V_i parameter on M class (M). Then it detects whether the luminary has to be individually regulated or entire group has to be selected for new regulation parameters, consequently changing the set P_{min} and P_{max} values. The actual time is obtained and it is checked whether it does not exceed t_n , in that case turning off the lighting, if not, the cycle is repeated after the delay of 10 minutes.

As dusk or glare sensor, the developed comparatively cheap RGBC integral chip based spherical sensor (6) can be used, which can determine the spectral content of the LED luminary (peaks of red, green and blue spectrum) and the relative amount of light, by some modifications it can determine the bright or dark time of the day, the increase of the reflected light, for example, approaching vehicle or wet asphalt in rain or snow conditions, therefore allowing to decrease the lighting level and creating additional energy savings, or otherwise increasing it and thereby improving the comfort of the driver [20], [21], traffic safety from the point of view of lighting.

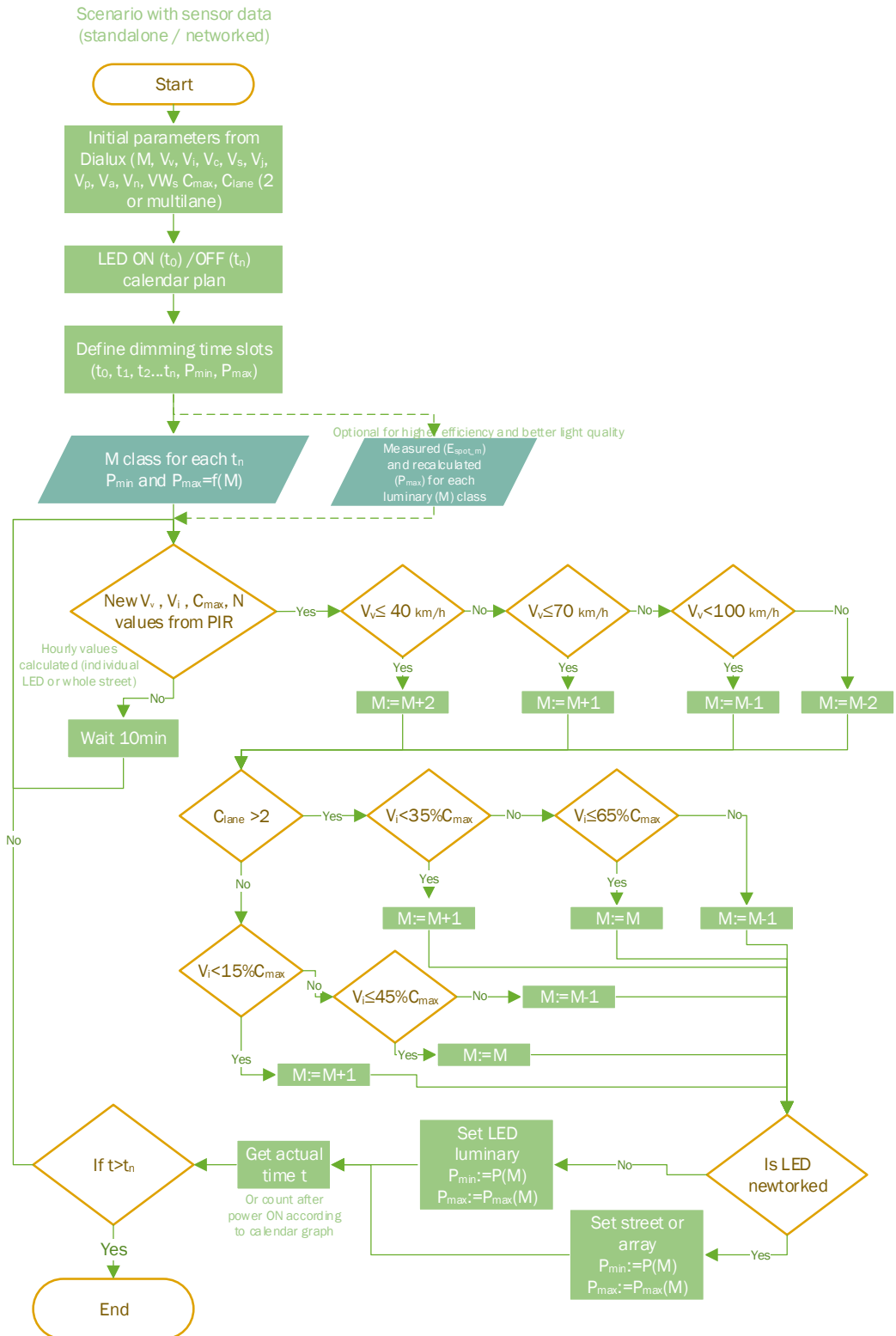


Fig. 5.4. LED luminary adaptive control algorithm for scenario with smart sensor data (standalone or networked regime).

The created dynamic management algorithm actually allows to manage lighting adaptively to the traffic intensity based on historical data, moreover, individual luminary and centralised system management can be provided for entire street or groups of streets over the ranges of several time zones of the day, therefore obtaining maximum efficiency and not reducing the traffic safety from the point of view of lighting.

Conclusions

The efficiency coefficients of smart LED lighting ballasts (including LED driver node and control node consumption) at nominal load parameters are above 0.80, which is proved by experimental measurements, where efficiency coefficient is 0.88 at the load of 150 W and input voltage range from 130 V to 256 V. Efficiency can be improved by choosing parts with specific nominal parameters and type of housing (for example, resistors, condenser, semiconductors) that would improve the efficiency by at least 2–5 %.

The created thermally compensated shunt allows to integrate the electricity consumption meter of LED luminaries in the PCB plate, thereby reducing manufacturing expenses compared to other solutions that use more expensive material with lower temperature coefficient of resistance. The novelty of the solution is proved by the received WIPO patent.

Smart street lighting systems equipped with LED luminaries and movement sensors allow to reduce electricity consumption by 69–73 % and reduce the installed power of luminaries by more than 40 %, systems without movement sensors allow to save approximately 51–72 % electricity per month, which is up to 60 % on average per year, and the installed power of luminaries can be reduced by 40 % approximately, thereby ensuring the same or improved lighting quality parameters if compared with the existing high pressure sodium luminaries.

Practical lighting measurements of new LED lighting systems with radar movement detection sensors show that the amount of actual lighting is on average by 63 % more than necessary, which consequently can be a potential electricity savings source. As a result of measurements of the smart lighting systems, it is comparatively easy to change the almost linear light output (lx) and power (W) relationship, ensuring appropriate lighting class (M) for each light pole.

The developed dynamic control algorithm allows controlling lighting adaptively to the traffic intensity, based on the historical data, moreover, it is possible to control individual lighting and centralised system – entire street or groups of streets.

In future research, it is planned to improve dynamic control algorithm, implementing predictive model and applying histogram coefficients, as well as to study replacement of the existing alternating current (AC) lighting system electrical grid with the direct current (DC) micro-grid, where it could be possible to reduce the existing electricity consumption by additional 5–10 % and obtain additional functionality of lighting infrastructure (for example, charging of electrical appliances, local solar energy transmission, communication network, etc.).

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