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Efficiency Analysis of Roadway Lighting Replacement in a Selected Polish Municipality

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Abstract: The paper addresses the problem of the efficiency of road lighting replacement in a selected municipality. The following question arose: can the replacement of lighting bring measurable financial benefits in the short or long term, and does increasing the comfort of road use in terms of lighting involve higher costs? During the global energy crisis, reducing the operating costs of road lighting has become the goal of many analyses and studies. Professionally selected lighting of streets and sidewalks is a factor that significantly affects the safety of road users. The problem of many studies is the omission of safety considerations, lighting comfort and budgetary possibilities of municipalities. The authors conducted comparative analyses of solution variants, examining both road lighting comfort and costs as an innovative element of research. The DIALux application was used to analyse the changes in road lighting depending on the luminaires used and the changes in pole spacing influenced by the height of the light point. Variant and scenario analyses were incorporated into the efficiency analyses, while the calculations themselves were based on detailed cost analyses with reference to Polish catalogues of material inputs and market prices. The authors conducted cost analyses of lighting dismantling and installation, including the subsequent operating costs over 20 years for seven variants of poles with their systems and four variants of luminaires. The results were compared with the existing lighting system in use. An original element of the study is the use of BIM analyses with design variants, combined with analyses of the technical condition of the existing lighting network and an illuminance analysis with estimates of the height and spacing of poles. Numerous studies indicate that it is very cost-effective to replace old lighting systems, especially those based on high-intensity discharge (HID) sodium lamps, with more modern LED lamps additionally equipped with twilight dimmers. The analyses also demonstrated that cost-efficient lighting replacement could go hand in hand with improved road lighting comfort without the need to incur additional costs, which is often overlooked in various studies. The analysis performed for a model lighting network indicates that savings of nearly 60% are possible over 20 years.

Keywords: efficiency analysis; BIM; LED; roadway lighting

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1. Introduction

Construction projects to improve the energy efficiency of street lighting systems are now a strategic element of economic, technological and social development. However, the decision-making process for selecting the optimal solutions to apply is very complex. An assessment of the economic efficiency of a building investment is becoming an essential element of all analyses performed prior to making a decision to construct. One reason is that certain investments, apart from economic savings, generate benefits for the environment, mainly ones that involve the modernization of how the demand for heat and electricity supplied to buildings is satisfied [1].

Several critical factors, such as difficulties in gaining access to credit by companies involved in the refurbishment of street lighting systems, budget constraints of municipalities, and unawareness of the actual energy and economic performance after a retrofitting intervention, require a decision-making approach that supports the municipal energy manager in selecting the optimal energy-efficient street lighting retrofit solution while looking not only at the available budget but also at the future savings in energy expenditures [2].

The authors [3] determined the actual energy savings when replacing high-pressure sodium (HPS) luminaires with light-emitting diode (LED) luminaires in street lighting by choosing an approach based on equal photopic or mesopic luminance levels. They considered the energy efficiency indicators of LED luminaires in both standard and reduced lighting regimes for different dimming scenarios. It was found that by using high-quality LED instead of high-quality HPS luminaires, energy savings can range from 31% to 60% when applying multi-stage dimming scenarios [3].

Similarly, another study [4] shows the benefits of LED technology and suggests that replacing traditional HPS luminaires with LED ones operated by a device with an integrated dynamic dimmer can save a significant amount of energy in the street lighting sector. The author demonstrated that the annual consumption of 2349.976 GWh with the use of HPS luminaires could be reduced by 47% to 1257.746 GWh per year. When a scenario with dynamic dimming is adopted, the energy consumed by street lighting can be reduced by up to 58% per year.

Light-emitting diode (LED) technology is widely used in street lighting. However, its implementation requires a large investment, making it a costly affair. Thus, replacing sodium lamps with LED technology requires a comprehensive budget analysis [5]. A study conducted by Lindawati et al. [5] aimed to calculate the probability of cost and energy reduction in the process of street lighting replacement with LED lighting. The authors analysed a 1470-metre-long road section with a total of 54 poles. According to the study, the initial investment is twice as high as traditional lighting, but adopting LED technology is more economical when considered over the long term. The cost of replacing the lamp is reduced by 51% over its lifetime. The use of LED technology in street lighting is, therefore, more efficient and has relatively lower running costs than traditional lighting.

According to [6], significant savings can be achieved by not only replacing traditional luminaires with low-power LEDs but also by providing streetlights with smart light controllers and network connectivity, allowing the introduction of sensible light intensity management and reduction in maintenance costs. By replacing traditional street lighting with LED lamps, utilities can reduce energy and operating costs by 46% or more [6]. Significantly greater savings can be achieved by controlling the light intensity and even introducing streetlight networking with a function to detect actual conditions (e.g., human and car traffic, weather) by temporarily dimming the lights, which can lead to overall savings of up to 80% or more. According to the authors [7], the IoT-based (Internet of Things) Master-Slave intelligent LED-light-controlling system installed in a parking zone with few people results in energy savings of 90%. The system has been adopted and installed so that the brightness of the LED lights in the featured zone can be changed simultaneously to reduce energy consumption, and the parameters of the LED lights can be set directly.

Upgrading public lighting systems by replacing existing luminaires with LED technology is a policy that many municipalities are adopting to reduce spending budgets as well as increase the environmental sustainability of a city. Furthermore, the introduction of innovative and flexible systems can be the first step toward a smart city approach. Retrofitting public lighting systems can increase energy efficiency and reduce maintenance costs and CO_2 emissions while improving lighting performance. On the other hand, it can significantly influence and change the night-time image and perception of urban and rural spaces.

The current energy crisis means that particular attention should be given to retrofitting and the economic benefits of road lighting control systems, assuming that such systems satisfactorily meet the visual requirements of pedestrians and drivers. The installation of new lighting systems or the retrofitting of existing ones requires careful consideration in terms of design configurations that would maintain the average illuminance of the road surface, the uniformity of illumination and the variability of illumination as needed while meeting national regulations and guidelines.

A separate but equally important topic is road construction safety, which is described in, e.g., [8,9] and road user safety, which is influenced, among others, by road lighting quality. Street lighting is an indispensable part of the night-time urban landscape. It is important for road safety, the visual comfort of users, crime prevention and increased perceived personal safety. The implementation and maintenance of an adequate street lighting service are very costly for municipalities and have a significant impact on their budgets [10]. At present, high-pressure sodium lamps are widely used in street lighting. This is in part due to their high efficacy and relatively long lifetime. Their use, however, comes at the expense of good colour rendering. The results presented in [11] consistently show that at comparable illuminances, people perceive areas illuminated with white light to be brighter, safer and more comfortable than the same neighbourhood illuminated with yellowish light. The results in [12] showed that from an environmental perspective, it is advantageous to upgrade frequently to the latest technology in order to capture efficiency gains. According to the authors, the cost-optimal strategy is frequently not aligned with the environmentally optimal management strategy. An area that needs to be further explored in the future, both in the context of lighting and other technological industries, is the mechanism for resolving trade-offs between economically and environmentally optimal decisions.

The authors [13] analysed the possible implications of retrofitting public lighting systems in small towns characterised by a prominent location, landscape context and widespread heritage. The paper evaluates the current lighting condition produced by traditional luminaires and the lighting condition produced by a retrofit proposal with LED sources from a case study located in the area of Maremma Grossetana in Tuscany. The authors compared the original and designed lighting solutions through simulations. They analysed the effects in terms of lighting and energy performance, as well as the implications for altering the nightscape. The results obtained by the authors confirm the positive impact of energy-efficient lighting systems on lighting performance, energy consumption and the perceived visual image of places.

To determine an approximation of the relevant road surface illuminance parameters, the authors [14] conducted photometric simulations of road lighting with photometric data tables of high-pressure sodium (HPS) and LED lights. The tests were performed for different power ratings for a given set of luminaire mounting height, road width, pole spacing, sag and slope values, and a mathematical model consisting of six equations derived by multiple linear regression with appropriate predictor variables was presented. The study, which focused on investigating the possibility of retrofitting conventional road lighting luminaires with LEDs, ultimately demonstrated environmental and economic benefits, primarily a short payback period, a high savings-to-investment ratio and electricity savings.

The researchers in [15] note that the initial cost of LED luminaires is significantly higher than that of other technologies and that investment costs can be a barrier to implementation. The paper discusses the adoption of LED luminaires to replace conventional lamps in public lighting systems in Rome (Italy), calculating possible energy and cost savings.

The authors [16] compared the lighting quality between the HPS and the LED luminaires and found that the LED luminaires have higher overall and longitudinal uniformity and higher threshold increment values than the HPS luminaires due to better light distribution efficiency. They found that LED luminaires can achieve better visual and comfort performance. The results of the road lighting quality study conducted by the authors [16] indicate that the average illuminance and surround ratio values are not completely different when the properties of road surfaces change. The energy evaluation results demonstrate that the LED luminaire achieves the best energy efficiency—significantly better than a conventional HPS luminaire.

In another paper [17], the authors estimated the national benefits of energy efficiency improvements in street lighting systems based on a pilot project in the city of Jakarta and energy audits in the other three cities. The research results showed that electricity consumption reduction potential through energy efficiency improvements could reach even 2.1 terawatt-hours annually.

As part of their research, the authors analysed the effectiveness of road lighting replacement in a selected municipality in Poland.

The scope of the topic covers the following issues:

- Analysis of the technical condition of the original lighting system, based on an assessment of the wear and tear of the lighting network;
- Time and cost analysis of variants of the technological concept of replacing the abovementioned system with a new one;
- Light intensity analyses were performed using Building Information Modelling (BIM) software;
- Estimate and description of possible benefits resulting from the lighting system replacement and analysis concerning the advisability of this undertaking.

The following objectives will therefore be fulfilled in the paper:

1. Development of a design for the street lighting system replacement in terms of the construction work;
2. Cost-effectiveness analysis of considered variants of the construction project, including time and cost of retrofitting, as well as the road user comfort due to the selection of spacing, the height of poles and luminaires influencing light intensity.

The unique element of the paper is a comprehensive approach to the topic of road lighting replacement involving the demonstration of a decision-making system based on time and cost variants with lighting analysis. All analyses are based on a BIM model of the road section concerned, including lighting, which provides information on time, construction and operating costs.

2. Materials and Methods

The Adopted Method of Analysing the Effectiveness of the Road Lighting System Replacement and the Comfort of Its Use

The analysis aimed to test the cost-efficiency of the lighting system replacement and the lighting comfort. The authors conducted comparative analyses of solution variants, examining both road lighting comfort and costs as an innovative element of research. The DIALux application was used to analyse the changes in road lighting depending on the luminaires used and the changes in pole spacing as influenced by the height of the light point. Variant and scenario analyses were used in the efficiency analyses, and the calculations themselves were based on detailed cost analyses with reference to Polish catalogues of material inputs and market prices. The authors conducted cost analyses of lighting dismantling and installation, including the subsequent operating costs over 20 years for 7 variants of poles with their systems and 4 variants of the luminaires used.

Figure 1 presents a simplified diagram of the procedure.

The first step was to define the purpose of the analysis. It could be, for example, to reduce energy costs, replace an old system due to excessive technical wear and tear or improve the comfort of road lighting. In the case of the study under discussion, the aim was to improve lighting comfort combined with the replacement of part of the lighting connected with the reduction in electricity consumption costs.

The next step was to analyse the technical condition of the existing road lighting network in the municipality and the energy currently used. As a result of the analysis, the technical condition should be presented along with the number of poles requiring immediate replacement and those for which it is cost-effective. The number of poles to be replaced was limited by the budget available to the municipality for this purpose.

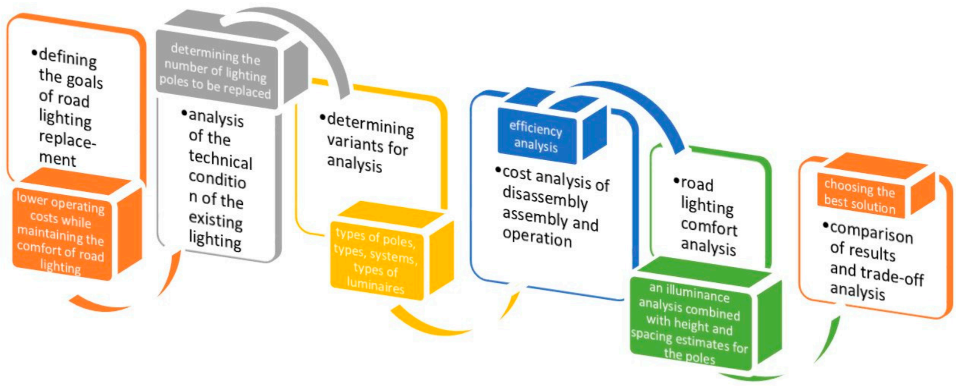


Figure 1. A simplified procedure in the method for analysing the effectiveness of road lighting system replacement and user comfort (source: original work).

The third step was to rank the variants of the new road lighting, i.e., the types of poles, systems and luminaires, resulting from the cost analysis. The analysis relates to the number of poles to be replaced, determined in the second step. The third step is essentially related to the next step, i.e., the road lighting comfort analysis. The analysis covers a number of pole parameters and their impact on lighting quality, such as pole spacing, the height of the light point, the length and inclination of the extension arm, etc. The result of the analysis is the changes in roadway lighting depending on the luminaires used and the changes in pole spacing with regard to the height of the light point.

The final stage was to choose a compromise solution between the lowest cost of dismantling the old light posts, installing the new ones and the operating costs of the new system and the resulting road lighting comfort. The results of the analysis are practical—they allow decision-makers to choose the best solution in terms of two important criteria—cost and lighting comfort.

3. Results

3.1. Analysis of the Existing Lighting System in a Selected Municipality

The analysis of lighting replacement should start with analyses of the technical condition and the number and types of lighting currently in use. The analysis of the number and types of lighting poles installed in the municipality is presented below. One can obtain the number of street lighting poles from an inventory compiled in the municipality or conduct a site visit. In general, it is also possible to automatically verify and identify poles. The paper [18] presents an approach to the automatic recognition of street lighting poles based on mobile LiDAR data. In the method, point clouds were initially divided into above-ground and non-above-ground structures, and then by using the Euclidean distance clustering method, the non-above-ground point clouds were grouped into a series of clusters. The information on shape and intensity was also taken into account. In the end, a method based on GMM (Gaussian mixture model) was used for cluster modelling, where street lighting poles were recognised as compared to the street lighting pole models from the database created. The proposed method was tested, and experimental results show that the approach achieved a fairly high recognition rate of 90%.

There are 487 lighting poles in the municipality in question. These are mostly prefabricated reinforced concrete poles (367 units) installed back in 1978 when they replaced wooden poles. The remainder are spun poles (120) installed in later years (2009–2010).

There are 655 light points with a total capacity of 57.85 kW in the municipality. PHILIPS luminaires from the SGS-102 product family were used in the street lighting system in the municipality. The light source dedicated to this type of luminaire is MASTER SON-T high-intensity discharge (HID) sodium lamps. Both 100 W and 70 W lamps were used for lighting in the municipality. Most of the luminaires (511 units) were installed in 2009

(Table 1). The remaining luminaires were successively replaced between 2010 and 2013 (an average of 64 luminaires per year).

Table 1. Summary data on the age of luminaires.

Year	Number of Replaced Luminaires (Units)	Age of Luminaires (Years)
2009	511	13
2010	36	12
2011	36	11
2012	36	10
2013	36	9
Total	655	-

Table 2 summarises the costs of operating and maintaining the street lighting network.

Table 2. Operation and maintenance costs of the street lighting network in a selected municipality.

Year	Operating Costs	Scheduled Maintenance Costs	Additional Maintenance Costs	Total Costs
2019	EUR 46,709	EUR 6582	EUR 4246	EUR 57,537
2020	EUR 48,832	EUR 7006	EUR 2972	EUR 58,811
2021	EUR 50,955	EUR 7219	EUR 4671	EUR 62,845

The wear rate of the poles was assessed according to Formula (1).

$$S_{max} = \frac{W_{max}}{T} = \frac{44}{50} \times 100\% = 88\% \quad (1)$$

where:

S_{max}—wear rate of the oldest poles;
W_{max}—age of the oldest poles $W_{max} = R_o - R_m = 2022 - 1978 = 44$;
R_o—current year;
R_m—year of installation;
T—useful life of the poles.

The wear rate of the poles is quite high. As the oldest poles reach the end of their useful life, the older ones should also be replaced during the possible replacement of luminaires.

It is generally assumed that the depreciation time for high-pressure sodium discharge lamps is approximately 20 years. The average wear rate of luminaires was calculated using Formula (2).

$$S_{zo} = \frac{\sum_{i=0}^{n} \frac{W_i}{T_o} \times N_i}{\sum_{i=0}^{n} N_i} \times 100\% \quad (2)$$

where:

S_{zo}—average wear rate of the system;
n—number of replacement periods;
W_i—age of luminaires replaced in year I;
T_o—lifetime of the luminaries, it is assumed that T = 20 years;
N_i—number of luminaires replaced in year i.

By using the data collected in Table 1 and Formula (2), the average wear rate of the luminaires was calculated to be 62%. The calculated average luminaire wear rate indicates that the technical condition of the system is far from ideal.

3.2. Costs of Dismantling and Installing the Lighting Network for the Selected Options

One of the main objectives of this study was to analyse the feasibility and cost-efficiency of retrofitting the street lighting network. The following section presents a few selected pole and luminaire systems that are being considered as proposals for the extension and upgrade of the network. The authors considered factors such as price, quality, ease of implementation of the solution and the shortest possible execution time when selecting them while maintaining the parameters of the existing network, as well as the intensity and colour of the light.

Table 3 presents the pole variants adopted for the analysis as combinations of spun or reinforced concrete poles with selected types of structures and luminaires. The installation of light poles requires a suitable structure for them, i.e., a geotechnical structure to hold them in place and correct position.

Table 3. Pole variants selected for analysis.

Variant	Types of Poles	Type of System
V1	E-type spun concrete poles, e.g., EOP 9/2.5	Uo
V2	E-type spun concrete poles, e.g., EOP 9/2.5	Uos
V3	E-type spun concrete poles, e.g., EOP 9/2.5	Up
V4	ZN-type reinforced concrete poles, e.g., ZN 9/200	UO1/ZN
V5	ZN-type reinforced concrete poles, e.g., ZN 9/201	UB1/ZN
V6	ZN-type reinforced concrete poles, e.g., ZN 9/202	UP1/ZN
V7	ZN-type reinforced concrete poles, e.g., ZN 9/203	UP2/ZN

Table 4 summarises the pole installation costs for the seven selected options. The costs in Table 4 include direct costs (labour, materials, equipment) and indirect costs.

Table 4. Pole installation costs for the 7 selected options.

Name of the Variant	Number of New Poles (Units)	Installation Price per Pole	Installation Price of All Poles	Installation Time per Pole (h)	Installation Time for All Poles (h)
EOP poles in Uo system	367	EUR 1317	EUR 483,489	1.7	624
EOP poles in Uos system		EUR 1325	EUR 486,502	1.6	587
EOP poles in Up system		EUR 1345	EUR 493,759	1.8	661
ZN poles in UO1/ZN system		EUR 1159	EUR 425,643	1.5	551
ZN poles in UB1/ZN system		EUR 1163	EUR 426,999	1.4	514
ZN poles in UP1/ZN system		EUR 1134	EUR 416,531	1.6	587
ZN poles in UP2/ZN system		EUR 1140	EUR 418,731	1.6	587

Table 5 summarises the installation costs for the luminaires without and with twilight dimming selected for analysis. The number of luminaire points was kept unchanged at 655.

Table 5. Summary of luminaires with installation costs.

Variant	Luminaire Type	Price of Luminaires	Price of Luminaires, Including Installation
A1	BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp luminaire	EUR 239	EUR 286
A2	120 W 230 V 6000 K 13500 lm grey JASPER C82-JAS1-120DG-6K LED street luminaire	EUR 262	EUR 320
B1	BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp luminaire with dusk dimmer	EUR 359	EUR 438
B2	120 W 230 V 6000 K 13500 lm grey JASPER C82-JAS1-120DG-6K LED street luminaire with dusk dimmer	EUR 382	EUR 474

Table 6, in turn, shows the costs associated with the dismantling of a single pole.

Table 6. Material expenditure for dismantling a reinforced concrete pole per pole, taking into account the nature of the planned works.

Item No.	Specification	Units	Number of Units	Price per Unit	Price
1.	Labour	r-g	4.86	EUR 8.92	EUR 43.34
2.	Means of transport	m-g	2.01	EUR 18.28	EUR 36.74
3.	Mobile crane	m-g	2.05	EUR 33.27	EUR 68.20
4.	Logging truck up to 10 t	m-g	0.55	EUR 27.42	EUR 15.08
		Total			EUR 163.37

As 367 poles were dismantled and replaced with new ones, the final cost of dismantling amounted to 367 × 163.37 = EUR 59,955.22. The dismantling time for a single pole is approximately 1 h, giving a total dismantling time of 367 h.

Table 7 shows the total costs for the dismantling and installation of the poles for the different options.

Table 7. Total costs for installation and dismantling of lighting poles.

Variant	A1	A2	B1	B2
V1	EUR 924,411	EUR 946,191	EUR 1,023,429	EUR 1,047,087
V2	EUR 928,629	EUR 950,409	EUR 1,027,647	EUR 1,051,305
V3	EUR 938,788	EUR 960,569	EUR 1,037,806	EUR 1,061,465
V4	EUR 843,427	EUR 865,207	EUR 942,445	EUR 966,103
V5	EUR 845,325	EUR 867,105	EUR 944,343	EUR 968,001
V6	EUR 830,670	EUR 852,450	EUR 929,688	EUR 953,346
V7	EUR 833,749	EUR 855,530	EUR 932,768	EUR 956,426

The analysis indicates that the best solution according to the NPV criterion is A1V6 variant—BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp mounted on ZN reinforced concrete poles, e.g., ZN 9/202 with the UP1/ZN system.

3.3. Projected Maintenance Costs for LED Lighting

According to the manufacturer's declaration, savings achieved with LED lamps are up to 70% compared with the use of discharge lamps. As this is the upper limit of the potential savings, for the purposes of the study, it was assumed that after replacing the old luminaires with LED luminaires, energy consumption would fall by 55% (the average reduction value resulting from the tests of differences declared by dimmer manufacturers is about 15–25% savings compared to systems without dimmers) and, if automatic light intensity reduction is used at night, by 70%. The projected cost of electricity consumption in the first year after installation of the LED luminaires is estimated as follows:

$$\text{Energy price (Euro/MWh)} \times \text{Lighting time (h/year)} \times \text{Power (MW)}$$

It is also assumed that energy costs will increase in the same way as for discharge lamps, i.e., as a geometric sequence where each successive amount is 103% of the previous amount.

In addition to the monthly planned costs, the maintenance costs for luminaires also include additional costs, mainly depending on the wear and tear of the fixtures. It is assumed that the additional maintenance costs for new LED luminaires will be very similar to the corresponding costs for new HID luminaires. Like the energy consumption costs for a new network with HID luminaires, these costs will be calculated based on a decreasing geometric sequence.

The graph (Figure 2) illustrates the operating costs for the old system without investment costs and the operating costs for subsequent variants with investment costs.

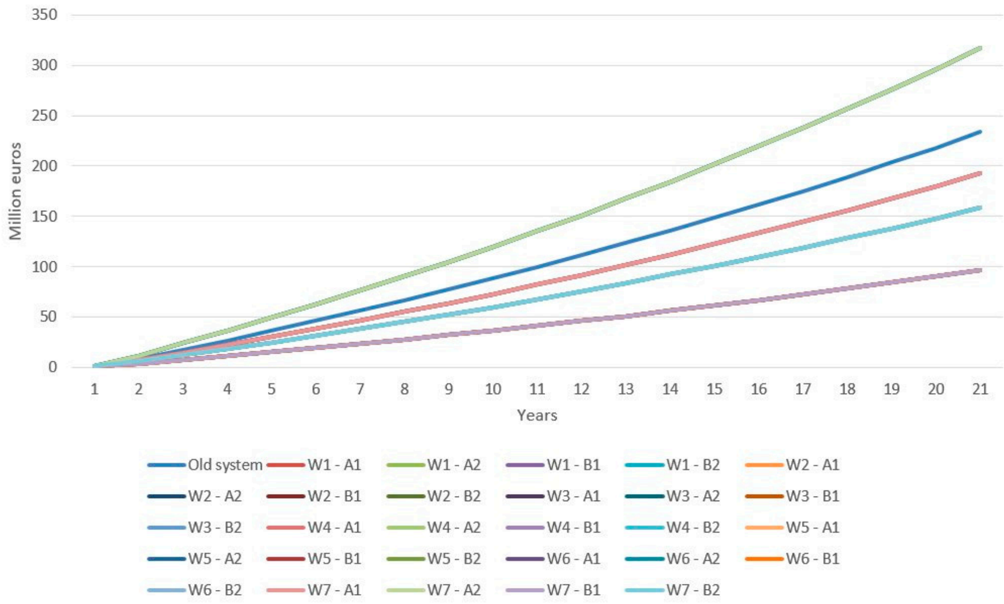


Figure 2. Investment and operating costs for street lighting installations (source: original work).

NPVs were also determined for the various options (Table 8).

Table 8. NPVs for the various street lighting replacement options.

Variant	A1	A2	B1	B2
V1	EUR 1,190,909,648	EUR 1,956,827,819	EUR 596,215,973	EUR 979,187,454
V2	EUR 1,190,913,743	EUR 1,956,831,914	EUR 596,220,068	EUR 979,191,550
V3	EUR 1,190,923,607	EUR 1,956,841,778	EUR 596,229,932	EUR 979,201,413
V4	EUR 1,190,831,023	EUR 1,956,749,194	EUR 596,137,348	EUR 979,108,829
V5	EUR 1,190,832,865	EUR 1,956,751,036	EUR 596,139,190	EUR 979,110,672
V6	EUR 1,190,818,638	EUR 1,956,736,808	EUR 596,124,962	EUR 979,096,444
V7	EUR 1,190,821,627	EUR 1,956,739,798	EUR 596,127,952	EUR 979,099,434

The best option in terms of investment and operating costs is the B1V6 variant—BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp with dusk dimmer, mounted on ZN reinforced concrete poles, e.g., ZN 9/202 with the UP1/ZN system.

3.4. Analysis of the Luminaires in Terms of Illuminance

In addition to installation cost and time, user comfort is also a significant consideration. By using the possibilities offered by Building Information Modelling (BIM) and DIALux lighting design software, an analysis of the road lighting was conducted for the variants under consideration. According to [19], BIM is a working methodology for the management of building or civil works projects in which all the agents involved in the process work collaboratively and throughout the life cycle of the building. The authors of the model can use it at various stages of design and construction.

Digital modelling tools in BIM enable one to create design variants. The data are represented geometrically and, using the right parameters, can be collated, sorted and displayed in a specific way while construction work can be planned. In addition to the properties of height, width and type of material used, geometry also has properties related to the manufacturer, the type of a given element, light intensity and the cost of a given element.

The BIM model is built from commercially available elements in BIM libraries. Such elements can be arranged in different variants, and it is possible to obtain information on the number of elements of a given type to be included in a road lighting project. The model will make it possible to approximate investment costs for given poles and luminaires.

The creation of variants in the model enables smooth fine-tuning of the design concept. The designer will be able to efficiently change the type of luminaires and supports. This application of the BIM model enables one to effectively perform a cost analysis of a given design solution. The tabular data are regularly updated due to the parameters used in the model geometry, such as the following:

- By changing a given luminaire for one-sided lighting, the costs of luminaires in the project will be updated for all lighting elements for the same number of luminaires, where a given luminaire also has a cost as a parameter;
- When replacing single-sided poles with double-sided poles, the cost of the option will change due to the use of a different way of road lighting; the number of supports will decrease, but the number of luminaires will also change.

Figure 3 shows design variants for spun and reinforced concrete poles using single-sided and double-sided luminaires.

An analysis of the road lighting will determine the number of lamps with given luminaires. Such an analysis can be performed in the DIALux application. However, one should always use applications that are compatible with each other. The paper [20] points out that not all applications are designed to cooperate due to different programming issues and data transfer methods. After importing data from the BIM libraries, it is necessary to check whether the virtual parameters are identical to the real ones. In this case, the individual lighting elements are imported into the application from the manufacturers' database. By assuming the appropriate density of road lighting elements, the analysis provides the following information:

- Spacing of the poles;
- Height of the light point;
- Length of the extension arm;
- Inclination of the extension arm.

Such information will enhance the quality of the design, but above all, it will ensure that the decision is based on a considerable amount of data. The designer and the client will know the spacing of lamps of a given intensity. The spacing of the lighting elements will be controlled in the design through intensity and cost analyses of different luminaire and support variants.

A comparative analysis of the different luminaires demonstrates how the roadway illumination changes due to the same geometrical parameters of the lighting element (Figure 4).

By using the same values for single-sided lighting, with the same pole spacing, the height of the light point, the length of the extension arm and the inclination of the extension arm, the BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp meets the lighting requirements and illuminates the intended roadway design better than the 120 W 230 V 6000 K 13500 lm grey JASPER C82-JAS1-120DG-6K LED street lamp.

An analysis of the Philips luminaire was then performed to show how the pole spacing changes due to the height of the light point (Figure 5).

The analysis indicates that the optimum pole height is 9 m. By adopting the same length and inclination of the extension arm in the different variants and with a variable value for the pole spacing and the height of the light point, the analysis shows that the sparsest possible pole spacing is 45 m. Therefore, the project used the fewest of them, which translates into the most optimal construction costs.

Figures 6 and 7 show the illumination for selected Philips and Jasper lamps. The analysis shows that the illumination for both lamps is similar. The illumination in the Jasper variant is more uniform than for the Philips lamp. The illumination in the Philips variant near the light source is stronger. For the entire road surface, the illumination with the Jasper lamp is more even.

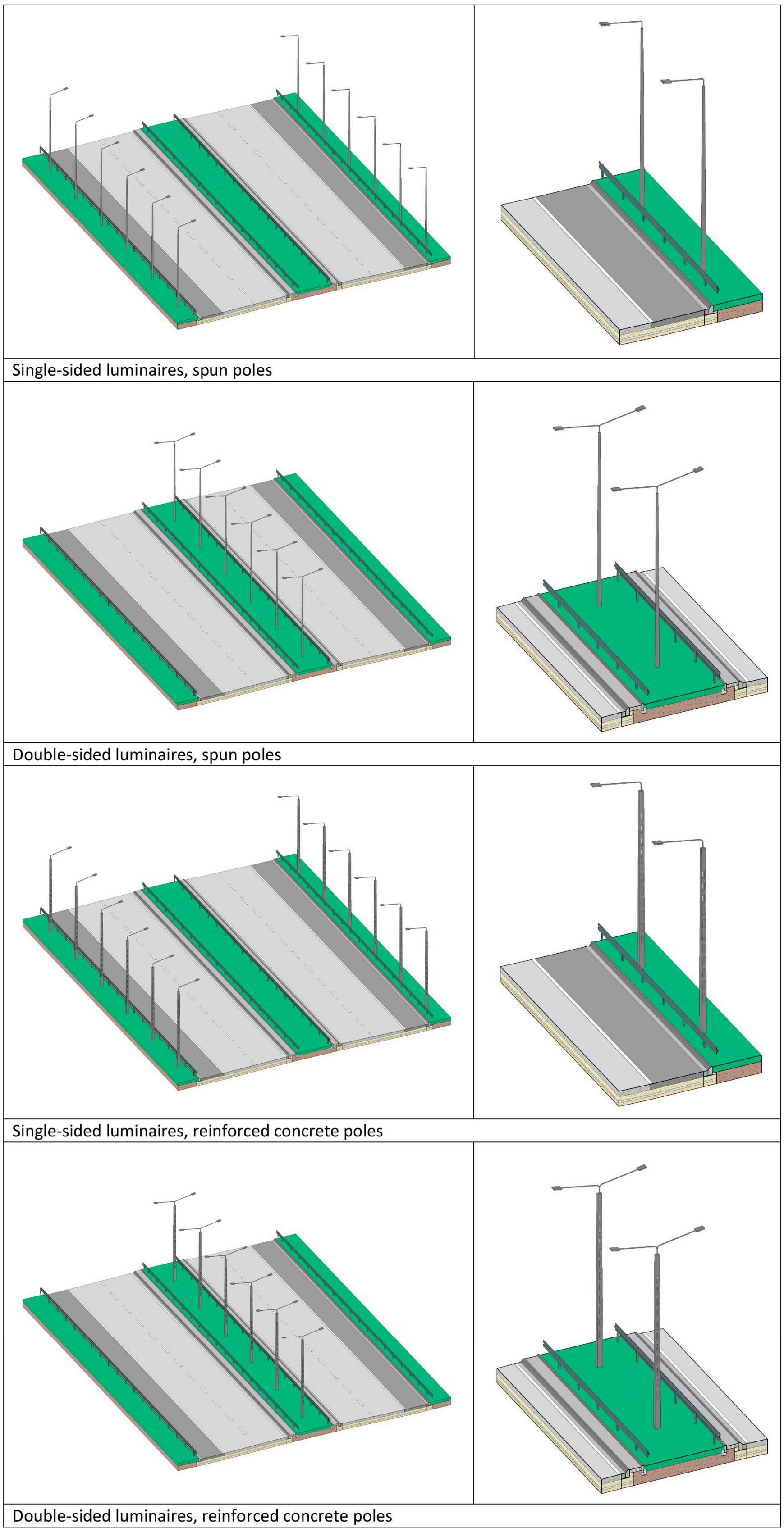
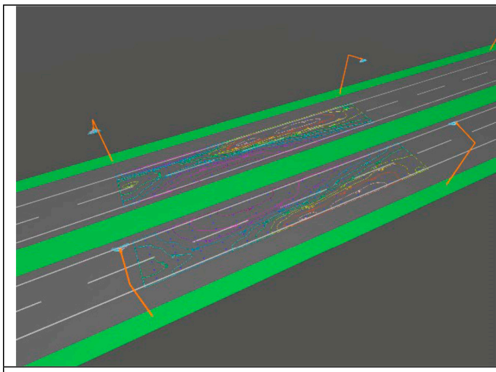
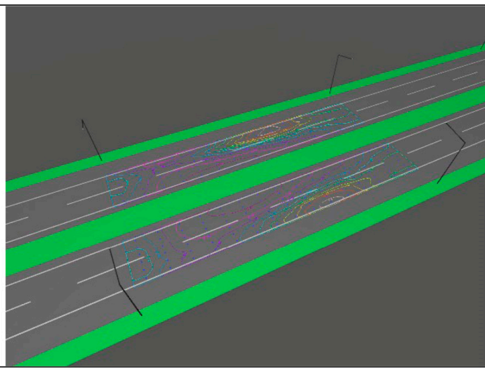


Figure 3. Design variants for spun and reinforced concrete poles with single-sided and double-sided luminaires (source: original work).

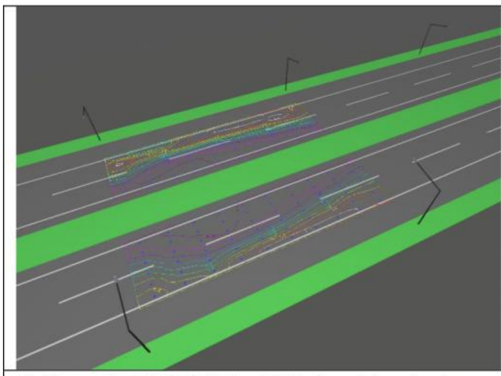


Philips - 73 W 10440 lm LED street lamp luminaire, pole spacing 45 m, height of the light point 9 m, length of the arm 3.3 m, inclination of the arm 13°

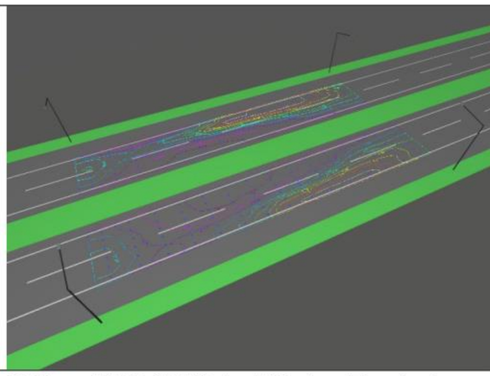


Jasper - 120 W 13500 lm LED street lamp luminaire, pole spacing 45 m, height of the light point 9 m, length of the arm 3.3 m, inclination of the arm 13°

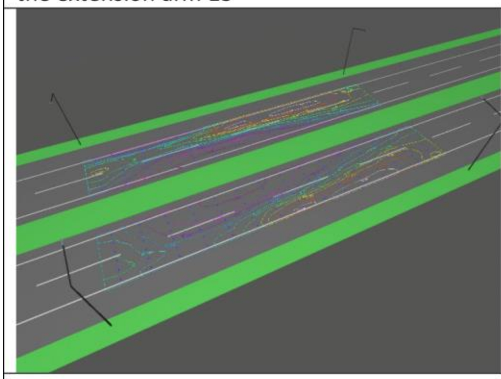
Figure 4. Changes in roadway illumination depending on the luminaires used (source: original work).



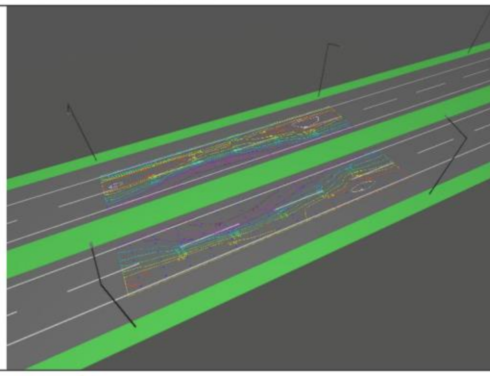
Philips - 73 W 10440 lm LED street luminaire, pole spacing 27 m, height of the light point 6 m, length of the extension arm 3.3 m, inclination of the extension arm 13°



Philips - 73 W 10440 lm LED street luminaire, pole spacing 44 m, height of the light point 8 m, length of the extension arm 3.3 m, inclination of the extension arm 13°



Philips - 73 W 10440 lm LED street luminaire, pole spacing 45 m, height of the light point 9 m, length of the extension arm 3.3 m, inclination of the extension arm 13°



Philips - 73 W 10440 lm LED street luminaire, pole spacing 41 m, height of the light point 11 m, length of the extension arm 3.3 m, inclination of the extension arm 13°

Figure 5. Analysis of the changes in pole spacing due to the height of the light point using the Philips street lamp luminaire as an example (source: original work).

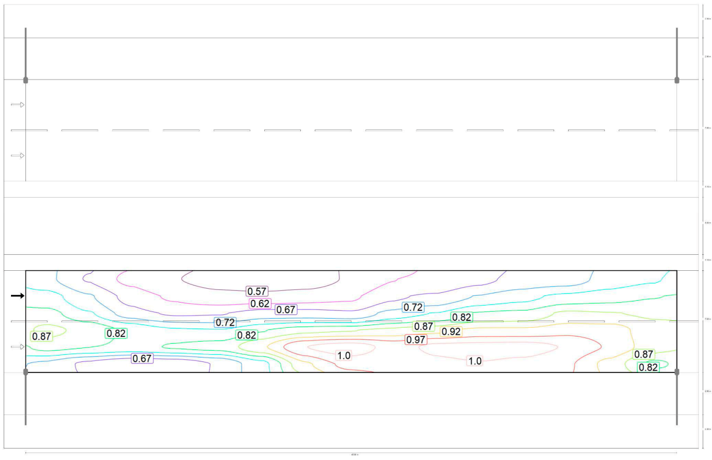


Figure 6. Jasper LED 120 W 13500 lm luminance for selected lamps in cd/m^2 units. Value chart and plan with projection of lighting distribution (source: original work).

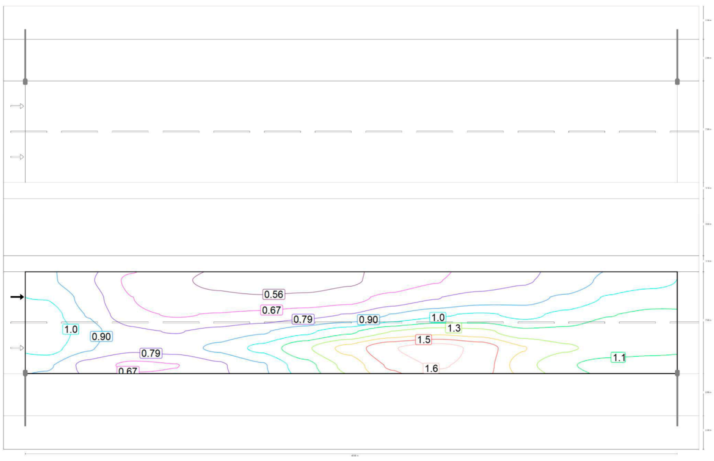


Figure 7. Philips LED 73 W 10440 lm luminance for selected lamps in cd/m^2 units. Value chart and plan with projection of lighting distribution (source: original work).

A pole height of 9 m and a spacing of 50 m were adopted in the economic analyses. Thus, the same conditions that resulted from the lighting intensity analysis were met. The relevant information is that Philips street luminaires are preferred.

In addition to design considerations, the model can also be employed during construction. The model indicates where exactly a given component will be installed. A work schedule created in a scheduling tool, such as Microsoft Project, can be linked to a model which includes the geometry of the elements. The schedule records which elements should be installed and when. The BIM model includes the following data about the structures:

- Production date, in the form of yes/no information;
- Cost of the item;
- Construction cost;
- Date of planned installation;
- Date of the completed installation.

Such an arrangement of parameters streamlines construction budget planning and ongoing changes. If certain items are not delivered or installed on time, construction times and schedules can be changed in the work schedule, and subsequent work stages will be updated. One plans the following stages of construction by integrating the model with the work schedule and cash flow.

Once construction is complete, the BIM model will be used for the potential replacement of existing luminaires or poles. The manufacturer's data, e.g., warranty cards, can be linked to the geometrical objects. The time of the last replacement or repair can be checked in the relevant parameter.

The BIM model created in the first stages of the investment will be used in subsequent stages of the development. This improves communication between various people involved in the investment process. Investment data are often located in different places in different files, which hinders editing or even finding it. In contrast, BIM technology provides a comprehensive database of the project and investment process in one place. In addition to the model itself, one can collect non-geometric data in the database: decisions, documents, certificates and other important statements that are accumulated during the process.

4. Results

When collating the results obtained from the analyses, the following should be noted:

1. The analysis of the total costs of installation and dismantling of the lighting poles indicates that the best solution according to the NPV criterion is the A1V6 variant—BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp luminaire mounted on ZN reinforced concrete poles, e.g., ZN 9/202 with the UP1/ZN system.
2. However, when considering a very significant factor of operating costs and adding them to the cost of installing and dismantling the lighting poles, the best solution is BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp luminaires with a dusk dimmer, mounted on reinforced ZN concrete poles, e.g., ZN 9/202 with the UP1/ZN system.
3. By using the same values for single-sided lighting, with the same pole spacing, the height of the light point, the length of the extension arm and the inclination of the extension arm, the BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp meets the lighting requirements and illuminates the planned roadway design better than the 120 W 230 V 6000 K 13500 lm grey JASPER C82-JAS1-120DG-6K LED street lamp.
4. The optimum pole height is 9 m.
5. By adopting the same length and inclination of the extension arm in the different variants and with a variable value for the pole spacing and the height of the light point, the minimum possible spacing between the poles is 45 m.

5. Discussion

The authors [21] developed a trust-based distributed sensor selection architecture for urban road networks under the requirement that the brightness of street lamps is maintained at the lowest admissible level. Simulations conducted to evaluate the potential energy savings have shown the efficiency of the proposed approach to be up to 70% when contrasted with traditional street lamp systems. In turn, the authors [17] state that, according to their research, the local government in Jakarta successfully reduced electricity bills for street lighting systems from USD 200,000 to USD 108,000 per month, i.e., by almost 50%. According to [22], LED ballast and control node regulation precision for a 'dimming profile' algorithm can be improved, as it shows rather wide variations in the real illumination values on the street and can give 8–10% energy savings. Campisi et al. [15] evaluated the replacement of 193,045 conventional street lighting luminaires with LED ones. They reported that the annual energy savings amounted to 70%. The paper shows that the project value obtained in the analysis adapted to the case study is higher than that obtained in the traditional analysis since the latter optimistically assumed a constant rate of electricity costs over the long lifetime of the LED packages. According to the literature review, the benefits can range from 50% to as much as 80% savings, depending on the selected lighting system and the use of automatic dimmers and motion sensors that switch on/off or regulate light intensity.

The authors' original research has shown the high efficiency of and quick return on the investment consisting in the replacement of road lighting poles. The results presented in the paper contribute to the general research on the efficiency of LED road lighting. However, it should be noted that road safety also constitutes a significant factor, which is often overlooked by many researchers when calculating the efficiency of solutions. They propose solutions consisting of switching off some street luminaires and introducing dimmable lighting and motion sensors. However, the statutory lighting standards in Poland and other European Union countries define the parameters that proper street lighting must meet. Maintaining lighting at the level set out in the standard helps to ensure the safety and comfort of the residents, road and street users in particular. It is, therefore, clear that seeking to reduce costs by, for example, partially switching off street luminaires not only fails to solve financial difficulties but also generates numerous complications and problems. Switching off every second or third luminaire, for example, will automatically result in non-compliance with the lighting uniformity and luminous flux parameters specified in the lighting standard. Therefore, the analysis aims not only to reduce costs but also to ensure lighting comfort and uniformity.

Many projects are optimized with digital tools. The aspect of roads is very important for any well-functioning city [23]. Properly lit roads create user comfort. With the right selection and consideration of optimum lighting solutions, future problems with the reconstruction and expansion of existing infrastructure can be avoided. Structural elements used during the construction of new roads can be reused for the installation of new luminaires in the future. Thus, it will not be necessary to demolish the entire infrastructure. Such possibilities for storing digital data, including historical records, and the easy replacement of selected road lighting elements without having to design them from scratch are offered today by the BIM models. The data used in the analysis can be stored in IFC files for future use [24]. IFC files contain the data provided by the commissioning authority and the author of the project. Standardisation should be taken into account when creating IFC files as it is the standards that enable the necessary data to be accessed and used efficiently. Data digitisation enables the preparation of variants quickly and efficiently [25]. With the available price lists and product information, one can complete the parameters in Revit or DIALux. Such data can be collated and recalculated, and conclusions can be drawn from it and used appropriately during construction. This prevents unnecessary on-site errors, typographical mistakes or time-consuming manual work in classic applications.

As the example of the tram line in Bologna shows, BIM technology can be used in many aspects of project design and planning [26]. Not only did the 3D modelling allow for a lighting analysis, but it was also possible to create 3D models of existing lines and compare them with the new ones, combining the installation model with the road model for complex construction works. BIM-based applications for lighting analysis are increasingly advanced. This is demonstrated in the paper [27], which discusses new possibilities for obtaining accurate data for a planned investment. With accurate lighting analysis, the designer will be able to apply the most suitable product to the site. The right choice will result in a reduction in energy consumption and an increase in quality of life. Therefore, efficient solutions should be sought and presented while simultaneously leaving it up to the decision-makers to select the most appropriate solutions in terms of their financial possibilities as well as luminous flux requirements related to traffic volume, road width, spacing and height of poles, etc.

6. Conclusions

Road lighting efficiency analysis is a necessity, especially in the face of rising energy prices. The use of BIM-based analyses allows one to develop solution variants quickly and accurately. The optimum solution in the case study proved to be BGP292 73 W 4000 K 10440 lm IK08 IP66 LumiStreet Philips LED street lamp luminaires with twilight dimming, mounted on ZN-type reinforced concrete poles, e.g., ZN 9/202 with the UP1/ZN system (B1V6 variant) at a pole height of 9 m and a minimum spacing of 45 m (50 m spacing was adopted).

The ongoing repair and maintenance costs of the existing network relative to the proposed use of the B1V6 variant were found to be significantly higher. Ultimately, with the use of twilight dimmers, energy consumption costs could be reduced to 41% compared to the cost of the old lighting system over 20 years.

An additional advantage resulting from the analysis methodology is the selection of the variant with better illumination (which also proved to be the cheapest variant in this case). The analysis, including a lighting comfort evaluation, addresses both road safety and the municipal budget.

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