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Multi-agent system supporting automated GIS-based photometric computations

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Abstract

The growing share of LED light sources in outdoor lighting enables developing street lighting solutions characterized by high energy efficiency. It is accomplished by replacing high intensity discharging lamps with LEDs and implementing various control strategies. It was also shown that a well tailored lighting design may significantly decrease the power usage. To apply this method in large projects, however, the computationally efficient approach is necessary. In this article we propose the method of energy efficiency optimization relying on a multi-agent system framework which enables scalable computations capable of handling large-scale projects. The case of a real-life optimization is also presented in the paper.

Keywords:

1 Introduction

One of the most significant challenges in all domains of technological development is the energy demand growing continuously. There are several major technological approaches to that issue such as looking for renewable energy sources (including energy storage) or improving energy efficiency of main power consumers. Roadway lighting efficiency in urban spaces is an important case of the problem. As stated in Northeast Group report [4] the number streetlights installed in the world is estimated to increase by 60 millions and reach nearly 340 million by 2025. In terms of the money spent for electric energy it gives the expected annual energy costs \$23.9 billion to \$42.5 billion by 2025, dependently on the assumed operational power. Those numbers show that optimization of street lighting installations has to be taken into account in the context of power management in the cities.

Among the various methods aiming at decreasing energy usage of street lighting installations two have to be pointed. The first one is based on using LED light sources instead of high intensity discharging (HID) or metal halide lamps. The second one, relying the LED technology, is based on optimization which aims at adjusting consumed power to the lowest level complying

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with the lighting standards requirements. The result of an optimization are, dependently of the retrofit scope, optimal settings for such parameters as fixture model, arm length, pole height, fixture's tilt and dimming. Since the consumed power decreases with increasing dimming level, the last property is crucial for a quality of final result.

The most common approach to creating a lighting design is a kind of trial-and-error procedure. A human designer prepares "manually" a project and next verifies it against some criteria. In the considered context such a criterion is energy efficiency of an installation. The above verification is supported by software [3, 14]. If a project check fails then a new (modified) configuration has to be examined.

In the above process some simplifications related to the road and installation layouts are made. In particular, it is assumed that the both are uniform.

In the international project *Products and Services of a Living Smart Energy City Lab* [7, 6] we showed that replacing "manual" trial-and-error process with regular computer-performed search enables obtaining statistically 8% reduction of the energy usage for sodium-vapor lamps. It is possible thanks to iterating over all available configurations.

Introducing simplifications related to the road and lighting installation layouts leads, however, to decreased energy efficiency of projects being created. It was shown in [13] that taking into account actual deviations from uniformity, i.e., a photometric design optimization made on the basis of precise, geodetic data (in the sequel referred to as GIS data - Geographical Information System) instead of uniform ones (e.g., averaged lamp spacing or road width) yields the power usage decreased by 15%. GIS data can be provided by mobile mappers or taken from already existing sources like CAD files. This approach will be referred to as a *customized design*. Although the customized design produces high quality solutions it operates on raw data (GIS-based) rather than on the calculation-ready, uniform scenes.

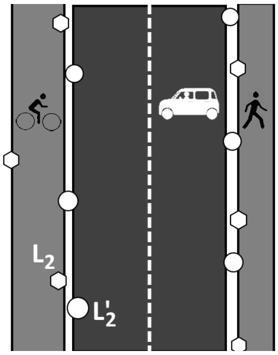

Figure 1: The sample road layout: bike lane, single carriageway and walkway. Circles mark street luminaires and hexagons denote park ones

Those raw data includes both area and luminaire coordinates which require appropriate preprocessing: identifying particular areas (walkways, roads, bike lanes, squares), establishing suitable calculation fields ascribed to them (Figure 1) and determining relevant luminaires (e.g., excluding park luminaires in a case of roadway lighting calculations). It is a critical problem for a computing system: it can be unable to recognize correctly relevant areas and determine calculation fields.

The above issue get critical especially for large projects covering thousands of luminaires. None of market-available programs can perform such automated computations, especially for large-scale projects. On the other side, a manual check of all possible configurations even using any software is utterly unfeasible in a reasonable time.

In this article we propose the approach which supports such operations. It combines a graph formalism with agent system methods. Such a combination allows for automated, scalable and time-efficient photometric calculations required in large street lighting optimizations made prior to retrofit works, for example when old sodium lamps are to be replaced with new, LED ones. This approach can be applied to a customized design and make this method applicable in the practical use.

The paper's objective is presenting effective calculation method applied for such an actual data-based optimization made by agents. Thanks to this the time efficiency is improved by

Table 1: ME lighting classes according to EN 13201-2

class	L_{avg} [cd/m^2] [min.]	U_o [min.]	U_l [min.]	TI [%] [max.]	SR [min.]
ME1	2.0	0.4	0.7	10	0.5
ME2	1.5	0.4	0.7	10	0.5
ME3a	1.0	0.4	0.7	15	0.5
ME3b	1.0	0.4	0.6	15	0.5
ME3c	1.0	0.4	0.5	15	0.5
ME4a	0.75	0.4	0.6	15	0.5
ME4b	0.75	0.4	0.5	15	0.5
ME5	0.5	0.35	0.4	15	0.5
ME6	0.3	0.35	0.4	15	n/a

excluding a human designer from a configuration search process and energy consumption is reduced by preparing the well tailored and standard compliant, photometric projects rather than on a deep hardware upgrade. The method being presented in the article breaks the rule of a lighting installation design where some solution for a single lighting situation is proposed by a human designer and next, verified (using trial-and error method) against the standard-derived constraints.

2 Preliminaries and the state of art

2.1 Photometric computations

The roadway lighting is subject to regulations concerning various aspects of the street illumination. In European countries they are described by EN 13201 standards which define lighting classes for particular public spaces, performance requirements for them, introduce the methodology of computing and measuring photometric parameters, and so on. Two standards are particularly important in this article; EN 13201-2 (performance requirements) and EN 13201-3 (calculation of performance) [1, 2]. The EN 13201-2 standard specifies what are the obligatory performance values of certain photometric parameters. For example, Table 1 presents requirements of so called ME classes for roads (with motorized traffic). It introduces the constraints for the light reflected on the road surface (i.e.,luminance), luminance uniformity and others.

EN 13201-3 in turn gives the detailed algorithm of computing all parameters. This algorithm is used by all industry-standard tools which support photometric computations like DIALux, Ulysse, Relux, Agi32 and others

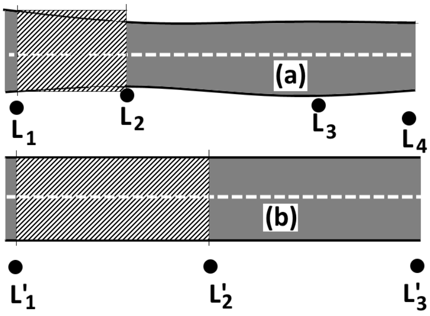

Figure 2: Actual road layout with physical luminaires $L_1, L_2 \ldots$(a) and its simplified form (b). $L'_1, L'_2, \ldots$ denote "averaged" luminaire positions. In both cases the sample calculation fields are marked with oblique hatching

(see [3, 14]). All those programs verify if a project complies with constraints given in Table 1 assuming uniformity of a lighting situation: evenly spaced and identical luminaires, uniformly distant from a carriageway and constant width carriageway. Calculations are made for a road section (also known as a calculation field) delimited by two subsequent luminaires (Figure 2b) which is representative for the entire road due to its assumed symmetry. Further calculating details which can be found in [2] will not be discussed here.

When performing computations for real life cases one assumes the most pessimistic conditions: the road width and lamp spacing are set to maxima or averages of actual widths and spacings respectively (see Figure 2). Thus the obtained results can be expected to be standard compliant[1]. The side effect of this approach is energy wasting and light pollution caused by over-illumination.

The proposed approach to improving energy efficiency applies the method discussed in depth in [13]. It uses the customized design based on actual GIS data, applied in the place of standard methods described above. For each point of a calculation field (Figure 2b) the relevant luminaires have to be identified (Figure 3) prior to photometric computations. According to the standard [2] it is accomplished by selecting all luminaires falling into the region of the size $17H \times 10H$, containing a calculation point, where H is a pole height. Note that such an identification requires processing raw GIS data and presumably some additional information concerning, for example, a luminaire type (park luminaires may be ignored when computing roadway lighting). Moreover, some luminaire fallen into such a region may be already processed. Then an actual calculation must not corrupt results obtained previously. The problems mentioned above influence complexity of a design task. In the further sections we present how a customized design can handle large scale computations, covering thousands of calculation fields.

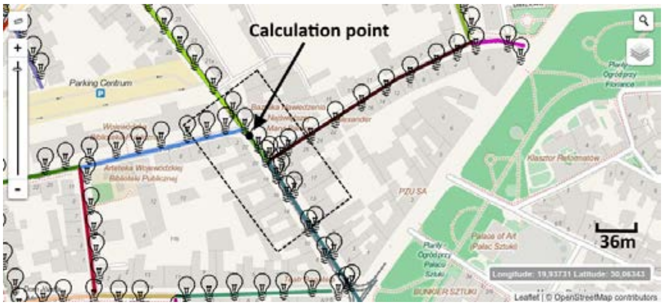

Figure 3: The real-life case of the sample calculation point. The dashed line delimits the region containing luminaires which have to be taken to compute luminance and illuminance in the point.

2.2 Graphs

To overcome the computing complexity issue described above the design problem has to be formulated using some formal model enabling computer processing. Such a model should be scalable and, on the other side, capable of hosting multi-agent system. The graph representations satisfy those demands. They are expressive enough to represent a broad range of systems [9, 5, 8]. Moreover, they were shown to be a suitable environment for multi-agent systems deployment [10, 11].

In the most intuitive, “naive” approach, streets, walkways, bike lanes etc. are represented by graph edges and road junctions by graph nodes. Node and edge labels can store either names or any identifiers of streets and junction ”points” (in fact, they are areas given by

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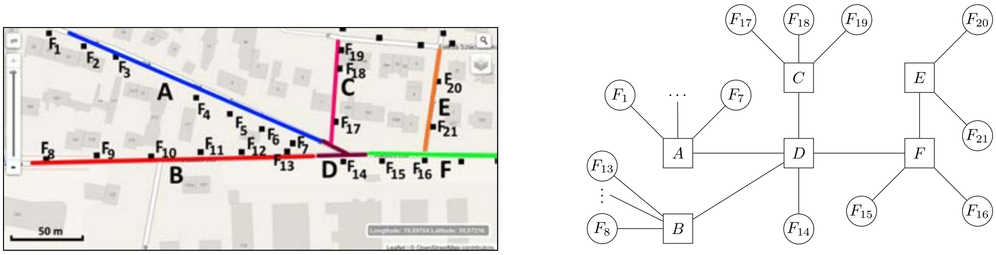
[1] In fact, aggregating with average may lead to violate the standard as shown in [13]

some bounding boxes rather than dimensionless points). All other data are held in attributes: some of node/edge ones are shown in Table 2. They group both street and luminaire related information. In the another approach, more suitable for practical use, graph nodes represent both calculating fields and luminaires (see Figure 4).



(a) A, B, C, D, E, F denote calculating fields; $F_1, F_2, \ldots F_{21}$ represent luminaires

(b) The graph representing the scene shown in Fig. 4a. Square nodes correspond to calculation fields, circled ones – to luminaires

Figure 4: The sample map and the corresponding simplified graph

A graph hosts multiple agents (see Section 4) which optimize particular installations street by street or, in terms of graph formalism, edge by edge (See Figure 8).

Table 2: The sample attributes ascribed to graph edges and vertices

Attribute name	Description
`bounding_box`	Array of 2D GIS coordinates
`lighting_class`	Lighting class (as in EN 13201:2)
`surface`	Reflective properties of the road surface
`luminaires`	Array of relevant luminaires (incl. full applicable data)

3 Calculation process

The considered problem may be described as follows. Given a city map consisting of two layers: a background layer including street layout data and an upper one containing positions of luminaires and the other related information. As noted in the previous section, a map is represented by some graph hence all important streets and luminaires data are stored either in edge/node attributes or directly in a graph structure.

Each luminaire is described, among others, by high precision GIS coordinates of a pole, in some geodetic coordinate system, e.g., UTM or WGS84. Street layout is also defined using geodetic coordinates. A task to be accomplished is twofold: extracting calculation fields from those raw data and making photometric computations on them. The former task is based on both map layers: it requires a street geometry to be known but also locations of particular luminaires which influence calculation field placement. The latter step is an optimization which can be described as searching for such values of luminaire adjustments which yield the most energy-efficient installation complying a mandatory (for an underlying street) lighting standard. Both steps are made interleavely in the course of processing.

The key step in photometric computations is determining a calculation field F with respect to considered luminaires. For roadway lighting situations it is accomplished by selecting two subsequent luminaires, say L_1, L_2. Figure 2 shows the fields for the customized (a) and standard (b) computational approaches. The next step is selecting all luminaires which have to be taken into account when computing photometric parameters on F and optimal adjustments for L_2 (L_1 is assumed to be already adjusted). After that a subsequent luminaire is taken (L_3), the new calculation field is set and the procedure is iterated. The detailed description of the process may be found in [13].

Note that the above schema may complicate when there are two luminaires, L_2, L_2' located close each other (see Figure 1). Then it is necessary to reject one of them on the basis of some additional information like pole GIS coordinates, fixture type, pole height, arm orientation with respect to the road axis etc. Such analysis is made by a *computing agent* described in Section 4.

When considering a large set of crossing streets two situations can occur: accessing a luminaire already processed (Figure 6a) and detecting two luminaires belonging to different series (Figure 6b).

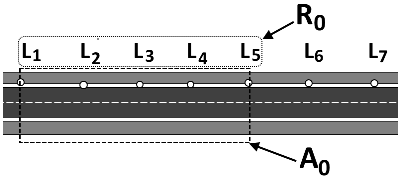


Figure 5: The initial phase of a computing process. R_0 is an initial row of luminaires and A_0 is an area grouping all neighboring communication routes

A principal computing process begins with a sequence of the five subsequent luminaires grouped in a row R_0, for which photometric computations are made (Figure 5). The calculating area (not to be confused with a calculation field), A_0, being a section of a roadway and neighboring walkways (or any other communication routes) corresponding to R_0 is determined on the basis of underlying GIS-based street layout. The result of computations are adjustments for luminaires in R_0 such that lighting standards requirements for A_0 are met and the power usage is minimized. After completing this stage calculations proceed iteratively: the next luminaire, l (L_6 in Figure 5), is taken, $R_1 = R_0 \cup \{l\}$, and photometric parameters are calculated for the extended area, $A_1 = A_0 \cup A(l)$, where $A(l)$ denotes an area influenced by the light emitted by l. Note that adjustments are calculated for l only and those obtained for R_0 are not changed anymore. All luminaires being already adjusted are tagged appropriately.

When following the scenario described above two situations can occur (see Figure 6):

1. A subsequent luminaire, say l_t, is already tagged which means that it was proceeded and adjusted accordingly (Figure 6a).

2. A subsequent luminaire, l_f, is located in a *forking point* where a new segment begins and l_f affects it (Figure 6b).

In the former case l_t is recalculated with respect to the area being currently processed. Having two sets of settings obtained (previous and actual ones, both are assumed to comply with the relevant lighting standard requirements) one selects the more restrictive ones.

Example. Let us assume, for example, that the carriageway of ME5 class was processed first (in Figure 6a the road along dark grayed symbols). In the result the power of l_t was adjusted to 100 W. Next, the photometric calculations for the neighboring route of ME3a class were made (the road along white symbols) and l_t as the last luminaire in the series was adjusted to 120 W. To ensure the standard compliance one selects from both wattage settings the latter one.

(a) Calculation process meets a processed and tagged luminaire (T)

(b) Calculation process meets a *forking point.* N symbol denotes the first luminaire in the new segment, C is a luminaire in the current segment

Figure 6: Two special cases in a calculation process. For both figures the bold arrows indicate processing order. White bulbs denote adjusted luminaires and dark grayed ones being currently adjusted. Non-filled bulbs stand for luminaires waiting for processing

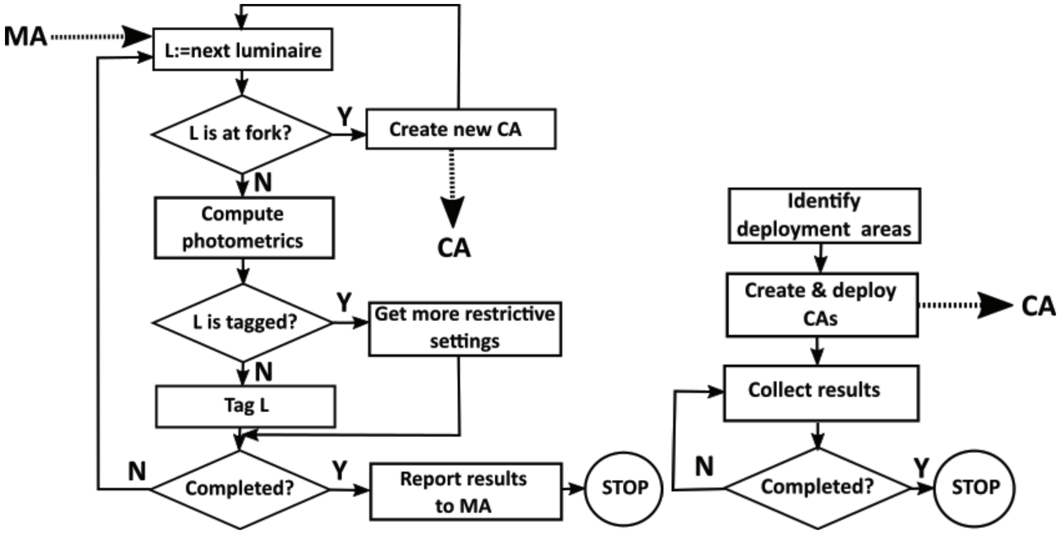


Figure 7: Multi-agent system activity schema. CA life cycle (left) and MA life cycle

In the second situation a new, separate process for the new segment has to be initiated. If applicable, the last processed luminaire gets shared as the first one in the new segment.

A process described in this section, applied to the large size problem requires involving a calculation paradigm allowing the parallel and scalable autonomous analysis and decision making. A multi-agent system is a suitable framework enabling that. In the next section a MAS structure will be discussed.

4 Agent system perspective

The multi-agent system architecture for the considered computations consists of two agent types only: *master agent* (abbrev.: MA) and *computing agent* (CA).

The role of a master agent, which exists in a single instance only, is decomposing a problem specific graph into a slashed form representing all sub-tasks to be processed (for a decomposition details see [10]). Moreover, an MA collects asynchronously sub-results incoming from computing agents (Figure 7-left). Those results may be supplied as messages containing JSON-formatted matchings of the form: $\langle \mathit{Calculation\ field\ ID}, \mathit{Photometric\ parameters}\rangle$. Optionally, an MA can redeploy a CA to restart some computations when a failure (timeout) is detected. An MA has to ensure that all luminaires are covered by photometric computations.

Computing agent which may exist in multiple instances is responsible in turn for executing a calculation processes as described in Section 3. In particular, a CA can create other CAs in "forking points" mentioned previously. The CA life cycle terminates ("`Completed?`" testing block in Figure 7-right) in one of the following circumstances:

1. All non-tagged luminaires have been already processed. It happens when either a CA met a tagged luminaire or no other lamp to be processed is left (the last luminaire has been just adjusted).

2. No solution can be found. Such a situation occurs when a problem of finding an optimal adjustments complying with a given lighting class cannot be found in the assumed search space. In this case a CA reports a problem to a MA. Then a master agent may restart calculations in a changed search space (e.g., with another fixture models or pole heights).

It should be noted that computing agents have to communicate each other during a calculation process. It is necessary because some luminaires which have to be taken into account by a given CA can be located in the area maintained by another CA. Then a request has to be sent to obtain required data. Yet another case is adjusting a luminaire located on a border of two (or more) areas maintained by two (or more) agents. In this case, in turn, all parties have to negotiate the adjustments satisfying lighting standards for each segment and minimizing the power usage. Note that it can be not a straightforward task due to the complex dependencies among luminaire locations, presence of shading objects and a resultant photometric performance.

Figure 8: The sample map with segments processed by agents

Figure 8 shows the map with multiple segments being processed by computing agents.

Table 3: Resultant installation power obtained in different computation approaches

Computing method	**Power required [kW]**	**Power savings**[3]
No optimization, standard calculations	275	0.0%
Optimized in standard calculations	253	8%
Optimized in customized calculations	234	15%

(a) Global view on a computing task as an MA sees it. The numbers in circles denote numbers of luminaires in particular subdomains. Black rectangle delimits area enlarged in Figure 9b

(b) Lighting installation layout from the perspective of a CA. Note that several CAs can operate in such a region

Figure 9: Computing task from the global and local perspective

5 Results

The proposed approach was applied to support the retrofit made in the city of Cracow, Poland. The goal of the project was replacing 3,700 HID fixtures with LED sources. Prior to that the optimization of adjustments was performed for all those luminaires. During that 2,000 fixture models[2] provided by several vendors were tested. Selected fixtures had to be matched appropriately to the area type (walkway, main road, park, parking zone and so forth). Besides a fixture model the inclination angle, dimming and other parameters were also varied while searching optimal configurations. The most common road layout contained the single carriageway with walkways at both sides (see Figure 1). Note that each of them had a separate lighting class ascribed. In terms of typical photometric computations the project covered approximately 1,800 calculation fields. Figure 9a presents a high-level view on several streets being processed (the OpenStreetMap underlay is used). Its zoomed section is shown in Figure 9b: single luminaires are marked as bulbs. The computing time required for optimizing luminaire adjustments for the case of sequential processing was $T_{seq} = 50\,\mathrm{h}\,24\,\mathrm{min}$ and the computing time for the case of an agent system using the reuse method [12] was $T_{ag} = 2\,\mathrm{h}\,5\,\mathrm{min}$. The speedup of a calculation process $s = T_{seq}/T_{ag}$ obtained thanks to using agents was $s = 24.2$.

Table 3 presents the results obtained for three methods of a lighting design. The first one is based on typical calculations as made by market-available software. The second one relies on standard computations too, but involves optimization of adjustments as well. In the third method the customized approach is applied. Namely, optimization performed on GIS-based street layout and luminaires locations data according to the algorithm presented in [13].

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[2] Precisely, this number refers to the photometric solids.

[3] Compared to non-optimized, standard calculations.

6 Conclusions

The presented calculating method combines preparation of well suited photometric designs yielding significant energy savings and scalable agent-based computations which allows for a time-efficient search over the entire solution space. It defines a multi-agent system framework which was successfully applied in real-life retrofit projects covering thousands of luminaires.

Computing agents involved in the above operations are responsible for optimal solution finding and local optimizations in "contact zones" where two or more lamp series meet.

The introduced methodology allows not only for optimizing roadway lighting installations but also enables application of adaptive control methods which fit roadway lighting performance to the actual requirements. These control methods rely on dynamic schemas where lamp dimming is set on the basis of an actual environment state reported by sensor layer (induction loops, ambient light meters, rain sensors and so forth). The role of the presented method is pre-optimization of all possible states of an installation. It reduces the power usage up to 15% when relying on the automated optimization and customized computation approach.

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