Estimation of Road Lighting Power Efficiency Using Graph-Controlled Spatial Data Interpretation

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Abstract. Estimation of street lighting energy requirements is a task crucial for both investment planning and efficiency evaluation of retrofit projects. However, this task is time-consuming and infeasible when performed by hand. This paper proposes an approach based on analysis of the publicly available map data. To assure the integrity of this process and automate it, a new type of graph transformations (Spatially Triggered Graph Transformations) is defined. The result is a semantic description of each lighting situation. The descriptions, in turn, are used to estimate the power necessary to fulfil the European lighting standard requirements, using pre-computed configurations stored in a 'big data' structure.

Keywords: Spatially-Triggered Graph Transformations · Big data · Lighting System · Spatial Data Analysis

1 Introduction

Design of street lighting installations is a compromise between the safety of road users and the operational costs. These costs are proportional to the amount of consumed energy, which directly translates into the amount of CO_2 emitted during its production. Recent studies also point out an additional (and unmeasurable) cost: the negative impact of light pollution during the night on humans and other organisms [6].

In Europe, the requirements for road and street lighting are set by the EN 13201 standard [5], and there are several software tools used to verify designs (prepared by a human designer) in that respect, such as Dialux[1] or Relux[2]. Unfortunately, it is not feasible for human designers to consider all possible configurations for a given set of street parameters, which leads to simplifications, such as averaging of values to reduce the number of cases to be considered. For instance, industry-standard designs do not take slight variations in pole spacing (e.g.: 33, 34, 32, 35 metres) into consideration, but instead use one, averaged

[1] https://www.dial.de/en/dialux/
[2] https://relux.com/en/

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value (e.g. 33 metres). The result of such an approach is increased energy consumption.

Let us consider the Polish market. In projects supporting lighting retrofit, the National Fund for Environmental Protection and Water Management requires that the energy consumption is reduced by at least 50%. A designer is able to provide such results using the aforementioned traditional design tools. However, there is room for improvement. Automatic photometric optimisation systems [11, 10], based on artificial intelligence solutions, can provide designs with energy consumption reduction of 70% to 80%. This has been practically proven in several lighting retrofit designs for cities of Tbilisi (100,000 lighting points), Washington (54,000 lighting points) and numerous Polish cities.

This additional 30% is very important from the ROI (return on investment) point of view. However, direct inclusion of consumption reduction requirements in public tender requirements is controversial. Since this value is always calculated using the power consumption of the initial installation, it is susceptible to inadequacies of that original configuration: if the road was underlit (and the EN 13201 was not fulfilled, which means new poles may need to be installed), the reduction factor will be lower (or there will be none at all); if it was overlit, this value may be much higher.

Thus, it is essential to provide city officials with means of obtaining a realistic estimate of the power required by a well-designed lighting installation and basing their requirements on that. However, executing a full design cycle during the project preparation phase is infeasible. Moreover, the photometric calculations alone may take days, even for an automated tool.

Therefore, we suggest that this estimation is carried out based on the analysis of publicly available map data. This paper presents a methodology that allows for such analysis and allows for quick estimation of the requirements based on pre-computed designs.

The structure of the paper is as follows. In Section 2, we characterise the factors which influence the design of street lighting infrastructures, and, as a result, their energy requirements. Section 3 describes the concept of spatially-triggered graph transformations (STGT), a mechanism used to identify spatial relationships among map objects and express them in a formal graph structure. In the following Section 4, we propose a data warehouse-like approach to store the results of photometric calculations and use them for quick estimation of the energy requirements of outdoor lighting. Finally, Section 5 provides concludes the presented work and provides an insight into works planned in the future.

2 Determinants of street lighting design and efficiency

The EN 13201 standard defines the rules assigning so-called *lighting classes* to individual lit areas [4], and specifies the required lighting parameter values (luminance, uniformity, etc.) for each class [5]. To fulfil these requirements in each individual street or sidewalk, many factors must be taken into consideration, including parameters of the area itself (e.g. its width), placement of the lampposts

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(e.g. spacing) and parameters of the infrastructure itself (e.g. pole height, arm length, fixture type, etc.).

Figure 1 provides a visual representation of some of these parameters, and their complete list is presented in Table 1. The rightmost column presents the maximum reasonable number of variants (granulation) for each parameter. Combinatorially, this leads to more than 2.75×10^{22} situations for one design (1.6×10^{21} is the product of the values; each combination shall be analysed for each surface type). For a large city, this may result in a need to prepare several hundred different designs, which is time-consuming. A possible solution would be to pre-calculate these values; however, with this many combinations, both the calculations and the storage of results seem infeasible. Fortunately, the number of possible variants can be reduced by introducing formal relations among these parameters, as presented in Section 4.

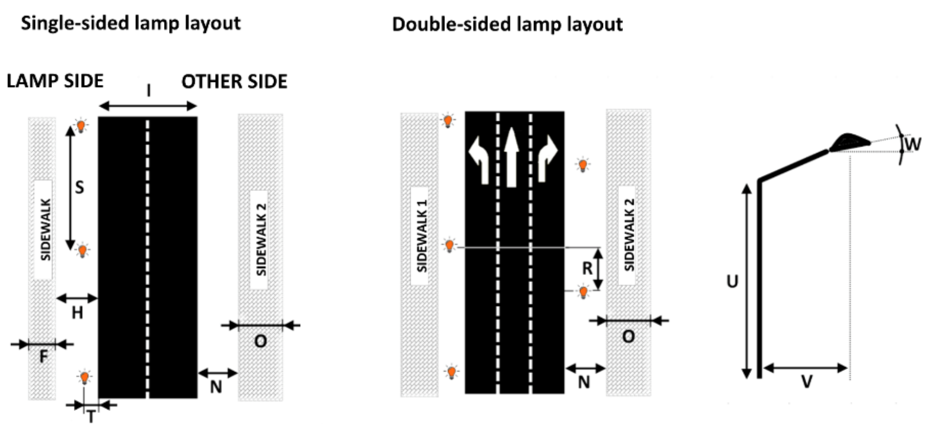

Fig. 1: street Situations

3 Modelling and interpretation of spatial relationships

The first, essential step in estimating the power needs of an area related to street lighting is identification and interpretation of the lighting situations, e.g. the values of parameters regarding the objects illuminated by a given lamp or series of lamps. As stated in the previous section, we aim at extracting as much information as possible using publicly available road maps, such as OpenStreetMap[3].

The street infrastructure (e.g. roads, sidewalks, cycle lanes, etc.) is represented in such sources as lines, described by the following attributes:

- the *spatial* component, e.g. the shape of the line,

[3] https://www.openstreetmap.org

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Variable label			**Description**	
Number of fixtures		E	Number of fixtures installed on the pole.	2
Sidewalks (lamp side)	Width	F	Width (in meters) of the sidewalk on the street side where an analyzed lamp is installed.	5
	Lighting class	G	Lighting class of a sidewalk.	12
	Distance from street	H	Width (in meters) of the gap between the street and the sidewalk.	6
STREET	Witdth	I	Street width (in meters)	26
	Number of lanes	J	Number of street lanes	5
	Surface type	K	Street surface type: from RTAB1 to RTAB16	16
	Q0	L	Value of the q0 factor for the street surface.	10
	Lighting class	M	Lighting class of the street	12
Sidewalks (lamp side)	Width	N	Width (in meters) of the sidewalk on the street side opposite to a side where an analyzed lamp is installed.	6
	Lighting class	O	Lighting class of the sidewalk	12
	Distance from street	P	Width (in meters) of a gap between the street and the sidewalk	6
Lamp arrangament		Q	Arrangement of poles/fixtures: single-sided, double-sided	2
Shift in fixture alligment		R	Shift between two opposite lamp rows	30
Distance between pools		S	Average distance (in meters) between poles	60
Pole distance from street		T	Distance (in meters) from the pole to street (set-back)	6
Pole hight		U	Pole height (in meters)	10
Arm lenght		V	Arm length (in meters)	6
Tilt angle		W	Fixture tilt angle (in degrees)	10
Fixture type		X	Fixture model	40
LDT file		Y	Name of a file containing a light distribution matrix.	10
Fixture power		Z	Fixture power (in watts)	20

Table 1: Parameters of the design designation

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- the *attribute* component, describing, among others:
  - object *type*: road (including road class), walkway (sidewalk, path, steps), cycle lane, etc.; this attribute is always provided,
  - *number of lanes*; this is provided optionally, but can be inferred from the road type in most cases,
  - *width* in meters; also provided optionally, but can be inferred from the number of lanes and road type.

However, the relationships between individual objects are usually absent in the source data; these include:

- *continuity* – denoting if a certain fragment of a road is a continuation of another one; this defines the *road network* structure, which can usually be inferred from the map (by identifying common nodes), but may also be missing e.g. due to editing mistakes,
- *intersections* – a concept similar to continuity, denoting if two objects intersect; it may represent the intersection of two roads, but also an intersection of a walkway and a road, which can (and should) be interpreted as a pedestrian crossing,
- *distance* – the distance between the closest points of two spatial objects (road to road, road to building, lamppost to road, etc.),
- *parallelism*[4] – identification of objects which run parallel to each other; this relationship is *never* represented in an explicit way.

The last mentioned relationship, parallelism, is crucial in many applications, including street lighting. This is because the same infrastructure is often used to illuminate different objects:

- a single lamp (fixture) often illuminates a road and its sidewalks,
- a single pole may be used to host lamps illuminating dual carriageways, or a road and a walkway separated by a median island.

3.1 Graph representation and generation

Identification of spatial relationships between objects can be a time-consuming task, as it involves the analysis of geometric shapes. Also, due to the huge number of possible combinations and the complexity of the process, such analysis may easily get out of hand when performed using only traditional tools, such as spatial databases (e.g. PostGIS[5]) or toolkits (e.g. GeoPandas[6]).

Because of this, we propose that the identified relationships are stored in a graph called *SRG* (*Spatial Relationship Graph*). After this phase, the 'raw' relationships will be further analysed to infer useful knowledge; in this case, the knowledge pertains to identified lighting situations, as described in Section 2.

[4] The use of this term may be confusing, at it is often used to describe parallel execution of logic on separate processors in concurrent applications. Please note that in this paper, it is always used to denote *geometric* parallelism of shapes.

[5] http://postgis.org

[6] https://geopandas.org

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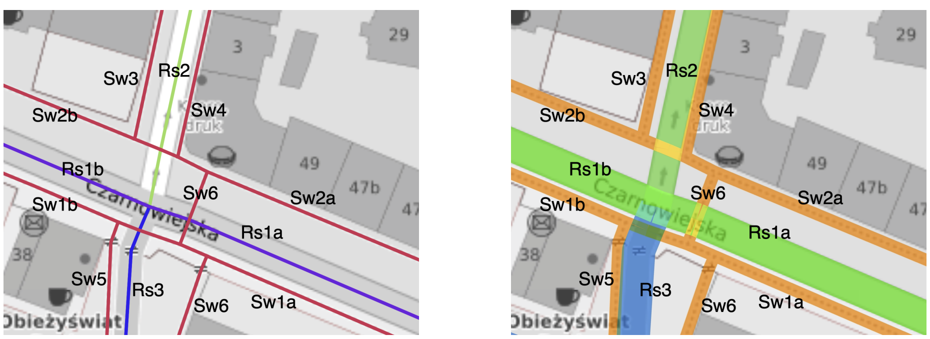
Spatially-Triggered Graph Transformations. For this purpose, we suggest the use of spatially-triggered graph transformations (STGT). The proposed mechanism is based on the formal approach supported by the well-known graph transformation structure [1, 8].

In essence, this methodology maintains a graph, where the structure and/or attributes are modified when:

(i) a certain spatial relationship is identified in the raw data, or
(ii) a specialised, semantic relationship is inferred from a more general one.

Its main advantage is that it allows the analysis to be performed automatically at a large scale (e.g. an entire city), while maintaining a form that can be reviewed and, if necessary, altered by the operator (as they are explicitly expressed according to their semantics). One of the major drawbacks of the approach presented in [9] (which doesn't use a graph to coordinate the analytical process) is the complex representation of both the analytic algorithms and their intermediate results. The presented STGT-based approach remedies this, allowing for easy backtracking and improvement.



(a) Initial state of map data

(b) Estimated object shapes

Fig. 2: Fragment of a city map used for spatial analysis

A Simple Example. Let us provide a simple, intuitive example. Figure 2a presents the initial state of the map data, as downloaded from OpenStreetMap. To maintain clarity, we shall focus on the part to the east of the junction, e.g. on objects Rs_{1a}, Sw_{1a}, Sw_{1b} and Sw_6. Already at this stage, we may infer the following relationships:

1. Sw_{1a} is parallel to Rs_{1a},
2. Sw_{2a} is parallel to Rs_{1a},
3. Sw_6 intersects with Rs_{1a}.

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Furthermore, having estimated the width of the individual objects, we may obtain their estimated shapes, as presented in Figure 2b[7]. This lets us supplement the identified relationships with the following attributes:

1. The average distance between Sw_{1a} and Rs_{1a} is 0.5 metres.
2. The average distance between Sw_{2a} and Rs_{1a} is 6 metres.

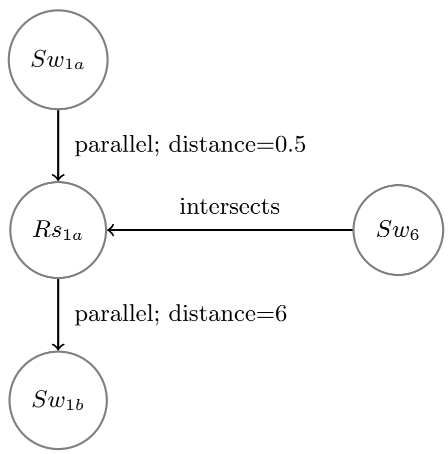

Fig. 3: Initial state of the SRG

Thus, the initial state of the SRG is presented in Figure 3. Subsequently, the following analyses and transformations may be performed:

1. If two objects are parallel to one another and their distance is less than 1 metre, we shall assume they are neighbouring.
2. If the distance is greater than 1 metre, we shall assume there is a green area (that does not need to be illuminated) between them.
3. If a walkway intersects with a road, we shall assume there is a pedestrian crossing and derive its offset (in metres) along the road.

As a result, we arrive at the specialized form of the SRG, the SRG_L (spatial relationship graph for lighting purposes), presented in Figure 4 This structure contains descriptions of all lighting situations in a form that allows them to be subjected to photometric calculations or, as described further in this paper, to look up the power values in a dedicated data structure.

[7] Please note that neither the algorithms used to detect the spatial relationships nor those used to estimate the road width are not presented here in detail. They are, however, a subject of individual research tracks; their results will be published in future papers.

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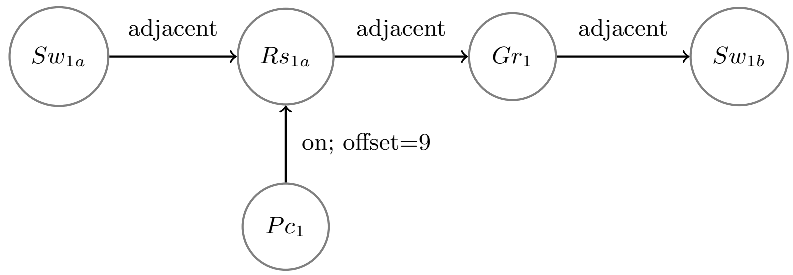

Fig. 4: The SRG_L graph, representing an identified lighting situation

3.2 Graph generation using a formal grammar

All of the transformations described at the intuitive level in Section 3.1 need to be performed in a controlled manner. The correctness of the proper graph generation is ensured by the graph transformation rules defined in a graph grammar. The grammar also allows for a hierarchical structure, as described later in this section. Such a grammar is defined as follows.

Definition 1. *A* graph grammar Ω *is a tuple:*

$$\Omega = (\Sigma_\Omega, \Gamma_\Omega, \Delta_\Omega, \Phi_\Omega, S_\Omega, \Pi_\Omega)$$

where:

- Σ_Ω *is the set of node labels,*
- $\Delta_\Omega \subset \Sigma_\Omega$*, is the set of terminal node labels,*
- Γ_Ω *is the set of edge labels,*
- Φ_Ω *is the set of transformation rules,*
- S_Ω *is the starting graph,*
- Π_Ω *is the graph grammar validation condition, that verifies the current state of the graph.*

We use Π_Ω as the validation condition of the graph grammar because sometimes it is necessary to execute a sequence of transformations and some of the intermediate states may not form a correct graph. In graph transformations, a common practice is to informally assume such a validation rule by introducing non-terminal nodes, as the final graph may not have any non-terminal nodes.

$\pi \in \Phi_\Omega$ is a transformation rule that transforms one graph into another one. π is denoted as a set of two graphs, lhs and rhs. For a given graph G, application of the π transformation rule is defined as follows:

- the lhs graph is removed from G creating G';
- the lhs graph is added to G' (but at this moment these graphs are separated);
- all edges in G that contain one of the nodes belonging to $V_{lhs} \cap V_{rhs}$ and the second to $V_G \setminus V_l hs$ are restored in $G' \cup rhs$;

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– all edges in G that contains removed nodes ($V_{lhs} \setminus V_{rhs}$) are removed.

Formally, the language generated by a graph grammar is defined as all validated graphs generated by a sequence of productions applied to the starting graph S_{Ω} (denoted as $L(\Omega)$).

In practice, we will execute only some sequences of a production – one that can be designated by analysing an independent, separate dataset. In this case, this graph grammar will be triggered by spatial relationships identified in GIS data.

Lighting design is usually based on the concept of a *road segment*, which is a uniform fragment of a street – one which can be described as a single lighting situation. The most complex representation of the segment is presented in Figure 5.

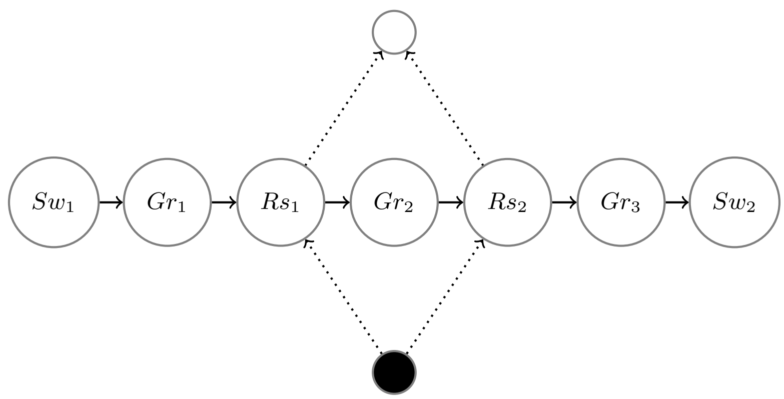

Fig. 5: segments

We will elaborate on how this extended form is achieved using the following example. Initially, a segment is represented by a single node labelled by Rs. As shown before, by analysing GIS data, we can identify spatial relationships between the carriageways side-walks and green (separation) areas. Later, these relationships are transformed into lighting situation descriptions. Several examples of correct representations are presented in Figure 6.

The examples presented up to this point only represent a single road segment, which is assumed to be of homogenous structure. As stated in Section 3, another spatial relationship detected among objects is *continuity*. Therefore, regardless of the internal structure of these segments, each segment may be linked with other segments with such a relationship. For clarity, this can be used to introduce a hierarchy in the graph structure.

The left-hand side of Figure 7 the top level of this hierarchy. Nodes labelled as SS (street segments) represent contracted road segments, where their internal structure is not visible. Since lighting of irregular areas (such as junctions or

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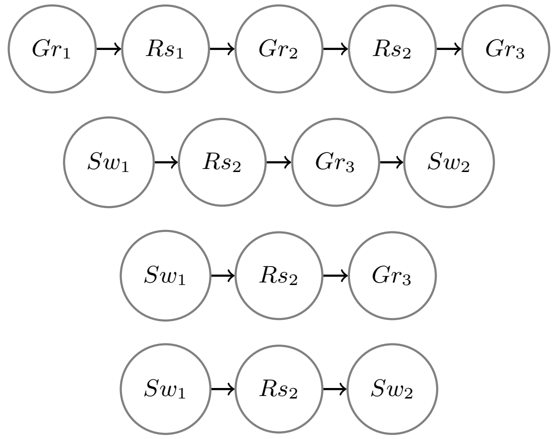

Fig. 6: Example representations of different lighting situations: a dual carriageway with surrounding green islands, a single carriageway with two sidewalks (one of them separated), a single carriageway with one sidewalk and one with two sidewalks on each side.

squares) is designed using a calculation methodology different from that used for regular roads or sidewalks. Nodes labelled as FF (free-form shapes) represent such areas (in this case, one may assume that they are junctions).[8]

The right-hand side presents the expanded form of the segment structure. The small black and white circles represent the input/output points to which the edges linked to a top-level segment are connected when the detailed view of the segment is presented (see [7] for a formal description of the concept).

3.3 Relation to previous results

Due to the flexibility of possible graph transformations, the proposed SRG structure can be easily used to obtain graph structures previously defined within our research.

For instance, it can easily be used to obtain the Semantic Environment Graph (SEG), described in [3].

Also, because the SRG maintains (and can even enhance) the network aspect of the map data, it can be used to automatically generate a Traffic Flow Graph (see [2]). This type of graph is used for modelling vehicle traffic to increase the feasibility of dynamic lighting control [12, 13] in areas with sparse sensor coverage.

[8] The estimation of power needed to illuminate them cannot be based on their length (W/m), but rather on their area. Its accuracy may be lower, but illumination of irregular areas constitutes a small percentage of the overall power consumption by city lighting.

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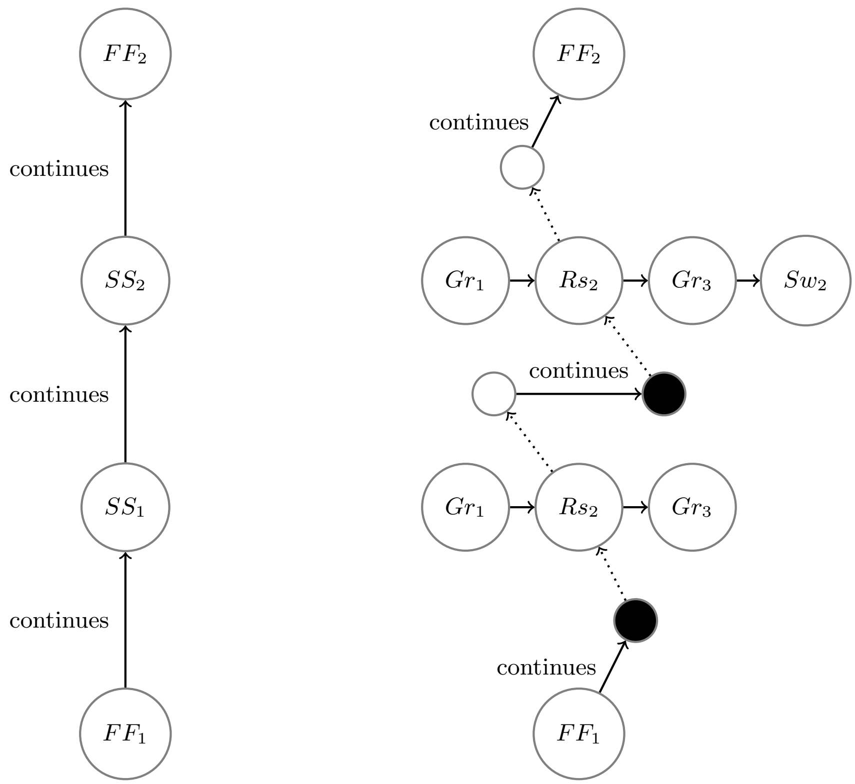

Fig. 7: Hierarchical view of road segments in contracted (left) and expanded form (right)

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4 Energy requirement estimation of outdoor lighting

STGT transformations allow us to generate SRG_L graphs, which describe lit areas in such a way that all factors significant for lighting design are present. To allow for a complete design, the formalism needs to be supplemented with lamp locations; however, here we do not aim at providing a detailed design, but to estimate the amount of energy required by a lighting installation to fulfil the lighting norms.

The concept of *lighting situations* (formally expressed with graphs generated by $STGT_L$) is key for this purpose. Each situation is described by a part of the graph presented in Figure 7 and additional parameters such as pole height, arm length, distance from the street, distance between the poles, lighting class and other non-structural information described in Table 1.

Therefore, we propose a multi-cube structure, LightCalc, where the main dimension is the lighting situation. For each lighting situation in LightCalc, we calculate and store a set of data, including:

- the parameters identifying the situation,
- the average power [W/km] in the most optimal (energy-efficient) design of this situation,
- the average power [W/km] after 5% and 10% disturbances are introduced into the values of parameters obtained for the most optimal design[9].

However, the issue of the size of the LightCalc cube needs to be resolved. As indicated in Section 2, the combinatorial space of all possible combinations makes the computations unfeasible. Fortunately, experience gained from projects involving large-scale photometric designs (Tbilisi, Washington) shows that in practice, the AI system generates and use only around 10–12 million lighting situations. This is a good size estimate of the LightCalc cube; it also means that if the set of parameter combinations is narrowed down to those which actually occur in real life (which is possible due to automatic analysis of lighting situations), both computation and storage is feasible.

The actual process of estimating the power requirements of city lighting installations involves the following steps:

1. The map data is analysed in order to build the SRG_L graph, as described in Section 3.
2. The LightCalc multi-cube is scanned for situations that are most similar to the identified one; the aforementioned susceptibility, modelled using 5%/10% value disturbances, is used to select a more 'robust' estimate if several possibilities are present.

[9] This value is stored to represent the susceptibility of the required power to parameter value fluctuations, which in turn can be used to estimate whether a certain power value is likely to occur in real-life situations, or if a greater margin should be assumed to make the estimate more realistic.

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The sum of the obtained values can be used as a real-life estimate of the power required to illuminate the set of streets under consideration. In practical situations, if the value is provided as the maximum power of installations offered in a public tender, a certain margin of error (e.g. 20%) should be added to compensate differences occurring from different (less-than-optimal) pole spacings or setbacks.

5 Conclusions

The paper tries to address the problem of estimating the energy required to illuminate a given area of a city according to the applicable standards (e.g. EN 13201). The presented concept is based on automatic analysis of publicly-available map data in order to explicitly identify semantic relationships among the represented objects. These are used to infer the parameters which influence the required lamp parameters (e.g. their power). Using this knowledge, the most probable installation power is estimated by reviewing previously calculated designs in a multi-cube structure.

The contributions of this paper are two-fold. On one hand, it proposes a method for consistent extraction of knowledge from spatial relationships identified between objects represented in map (geographic) datasets. A new type of graph transformations (Spatially Triggered Graph Transformation) is defined to coordinate and automate the analytical process and generate the appropriate data structure for lighting design.

The second contribution pertains directly to quick estimation of energy requirements of outdoor lighting. Instead of performing the time-consuming calculations on demand, the semantic relations expressed in the LightCalc multi-cube structure allow us the estimate the power of an optimally-designed installation using designs prepared for segments with a similar structure.

In practice, this task is very important for city officials. It lets them use a realistic estimate of the required power and compare it to the current, legacy installation in order to mitigate the risk of not meeting the power reduction factors required by funding agencies. It can also be useful to prepare realistic requirements in public tender procedures to enforce the proper quality of the offered configurations, e.g. by specifying their maximum total power.

This methodology could also prove useful for the funding agencies themselves, by letting them reformulate the environmental impact requirements imposed upon the beneficiaries. Requiring a certain reduction of energy usage in relation to the current installation favours cities with over-lighting, but hinders retrofit in areas where the lighting was inadequate (e.g. due to excessive lamp spacing, which translates to too few lamps).

Finally, it should be noted that the application area of the proposed spatially-triggered graph transformations (and the resulting semantic model) is much broader than just for optimisation of street lighting. A semantic description of an area is considerably easier to analyse than a set of shapes. This allows for planning and analysis, both on the micro and the macro level (e.g. to evaluate

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the availability of public transportation or green areas in relation to residential buildings).

References

1. Ehrig, H., Ehrig, K., Prange, U., Taentzer, G.: Fundamentals of Algebraic Graph Transformation. Monographs in Theoretical Computer Science. An EATCS Series, Springer-Verlag, Berlin Heidelberg (2006). https://doi.org/10.1007/3-540-31188-2
2. Ernst, S., Komnata, K., Łabuz, M., Środa, K.: Graph-Based Vehicle Traffic Modelling for More Efficient Road Lighting. In: Zamojski, W., Mazurkiewicz, J., Sugier, J., Walkowiak, T., Kacprzyk, J. (eds.) Engineering in Dependability of Computer Systems and Networks. pp. 186–194. Advances in Intelligent Systems and Computing, Springer International Publishing (2020)
3. Ernst, S., Łabuz, M., Środa, K., Kotulski, L.: Graph-Based Spatial Data Processing and Analysis for More Efficient Road Lighting Design. Sustainability **10**(11), 3850 (Nov 2018). https://doi.org/10.3390/su10113850
4. European Committee for Standarization: CEN/TR 13201-1: Road lighting – Part 1: Guidelines on selection of lighting classes. Tech. rep., European Committee for Standarization (Dec 2014)
5. European Committee for Standarization: EN 13201-2: Road lighting – Part 2: Performance requirements. Tech. rep. (Dec 2014)
6. Hölker, F., Moss, T., Griefahn, B., Kloas, W., Voigt, C.C., Henckel, D., Hänel, A., Kappeler, P.M., Völker, S., Schwope, A., Franke, S., Uhrlandt, D., Fischer, J., Klenke, R., Wolter, C., Tockner, K.: The Dark Side of Light: A Transdisciplinary Research Agenda for Light Pollution Policy. Ecology and Society **15**(4) (2010)
7. Kotulski, L., Wydawnictwa, A.G.H.i.S.S.K., AGH., W.: Rozproszone Transformacje Grafowe: Teoria i Zastosowania. Redakcja Wydawnictw AGH (2013)
8. Rozenberg, G. (ed.): Handbook of Graph Grammars and Computing by Graph Transformation. WSPC, Singapore ; New Jersey (Jan 1997)
9. Sebastian Ernst, Jakub Starczewski: How Spatial Data Analysis Can Make Smart Lighting Smarter. In: ACIIDS 2021: 13th Asian Conference on Intelligent Information and Database Systems. accepted for publication (2021)
10. Sędziwy, A.: A New Approach to Street Lighting Design. LEUKOS **12**(3), 151–162 (Jul 2016). https://doi.org/10.1080/15502724.2015.1080122
11. Sędziwy, A., Basiura, A.: Energy Reduction in Roadway Lighting Achieved with Novel Design Approach and LEDs. LEUKOS **14**(1), 45–51 (Jan 2018). https://doi.org/10.1080/15502724.2017.1330155
12. Wojnicki, I., Kotulski, L.: Empirical Study of How Traffic Intensity Detector Parameters Influence Dynamic Street Lighting Energy Consumption: A Case Study in Krakow, Poland. Sustainability **10**(4), 1221 (Apr 2018). https://doi.org/10.3390/su10041221
13. Wojnicki, I., Kotulski, L.: Improving Control Efficiency of Dynamic Street Lighting by Utilizing the Dual Graph Grammar Concept. Energies **11**(2), 402 (Feb 2018). https://doi.org/10.3390/en11020402

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