A Multi-Objective Mixed Integer Programming Model for Minimising Obtrusive Effects and Installation Costs of Night-time Lighting on Construction Sites

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Abstract

The increase in the rate of urbanisation worldwide has led to a boom in the construction industry sector in most major cities. To cope with the associated rising demand for further services and facilities, contractors find themselves frequently obliged to extend working hours on construction sites. Construction of major infrastructure projects, such as road works, is conducted at times of the day when less disruption is likely to result to the affected population. As a result, night work is now a common sighting on many construction sites. To allow for better vision for construction personnel on sites, floodlights are deployed during night work to light up work zones. There is an expense however to the adoption of construction lighting, particularly when considering the social and environmental impacts arising due to light pollution. In a residential district, and especially when infrastructure projects are taking place, the lighting system utilised on a construction site can be a cause of major disruption to the people and wildlife in the vicinity of the site. This paper attempts to model the problem of construction lighting through an optimisation model that minimises both construction light set-up costs and the maximum light pollution perceived at light-sensitive receivers. At the same time, the model ensures an appropriate coverage level to avoid impairing workers' vision on site. The developed formulations take the format of a Mixed Integer Programming model. An illustrative case study is applied to a construction project to demonstrate the applicability of the model.

Keywords –
Construction Lighting; Light Pollution; Multi-Objective Optimisation; Mixed Integer Programming; ε - constraint Method; Sustainable Construction Operations.

1 Introduction

With the rising tendency of extending working times in the construction sector, in order to meet strict deadlines imposed on project completion, the sight of construction work taking place during the night time has become a norm in many cities around the world [1]. Along with the increasing rate of urbanisation, the steady increase in population of urban cities prompts contractors to race in the delivery of projects, in order to meet the generated demand. To allow for a smooth execution of tasks during the night hours on a construction site, an adequate lighting system needs to be installed. One of the main issues addressed by governing bodies, such as the International Commission on Illumination (CIE), which set out lighting regulations, is the provision of a reasonable level of lighting such that workers' vision is maintained properly. At the same time it has to be ensured that the negative impacts from the lighting system adopted, on the neighbouring vicinity is kept to a minimum. Thus, in Australia, obtrusive effects resulting from the lighting plan implemented on a construction site must adhere to the guidelines provided in outdoor lighting standards such as AS 4282 [2]. It is also necessary that the enforced plan produces an adequate light intensity, as stipulated in AS 1680.5 [3], to allow for optimum working conditions on site.

The operational impacts of the lighting plan deployed during night-time construction are wide and varied. Some of the factors reported to be influenced on construction projects include cost, productivity and safety of construction tasks [4], [5]. Dealing with excess lighting and its ramifications on human health, as well as its effect on wildlife and on stellar vision, is necessary, given that light pollution is one of the fastest growing forms of pollution [6]. When discussing the health impacts of lighting the most prevalent effect of light exposure is the reduction in the production and secretion of Melatonin [7], [8]. Among the plethora of ailments found to be associated with Melatonin suppression in humans, we list the following: sleep disruptions [9], psychiatric disorders [10], abnormal adrenergic functioning [11] and an increase in the risk of cancer progression [12]. Documented nocturnal lighting effects on wildlife include alteration of migration, communication, mating and predation behaviour [13].

Various ways of optimising outdoor lighting parameters have been studied in the literature. Noor- E - Alam et al., [14], proposed a grid-based lighting location problem where mixed integer programming (MIP) models were developed to minimise the amount of darkness and excess supply of light in an open park. Optimising the design of specific parts relating to the luminaire itself has been attempted in order to minimise energy consumption and optimise light distribution [15]. Other topics related to the optimisation of light photometric factors include the problem of optimising road lighting distribution [16], and the optimisation of the height of luminaires to improve energy efficiency and satisfy target illuminance of demand areas [17]. Gómez-Lorente et al. [18] presented a multi-objective evolutionary algorithm which maximises the illuminance uniformity and the installation efficiency of roadway luminaires. Lai et al. [19] proposed a non-linear optimisation model to minimise the luminous flux of light settings in a long tunnel.

When it comes to construction lighting, studies have mostly concentrated on the optimisation of lighting for highway construction tasks. The work of El-Rayes and Hyari [20] focused on developing a framework, labelled as CONLIGHT, which incorporates different parametric elements that concern the design of lighting plans for night-time highway construction and rehabilitation projects. The same authors then implemented the framework in a multi-objective optimisation problem that incorporated the use of genetic algorithms, where the authors maximised average illuminance and lighting uniformity, while cost and glare were minimised [21]. Said and El-Rayes, 2010 [22] incorporated a light system optimisation module in a proposed multi-objective framework to optimise the security of critical infrastructure projects through site layout planning. Corcione and Fontana [23] focused on outdoor lightings; in particular the use of GA to optimise the lighting requirements in sport fields. Excessive luminance, causing discomfort to an observer, is addressed in many of the standards, through specified restrictions on luminaire's aiming direction with respect to the observer's line of sight [24].

On a construction site, mathematical optimisation has been employed in previous studies to minimise noise pollution and transport costs [25]–[28], with no mentioning of light pollution as an objective. Optimisation studies accounting for light obtrusiveness are mostly related to road luminaires where observers are taken as vehicle drivers [29], with little or no attention directed at limiting light pollution at other types of light sensitive receivers. As such, we propose a location model to optimise the location of floodlights around a construction site while ensuring that light intensities at light sensitive receivers, in the vicinity of the construction site, are kept to a minimum. Light related formulations have been obtained from light design standards, including AS 4282 [2] and CIE 150 [30].

Location theory has been extensively studied and applied to various problems in a variety of fields. A class of models that we adapt, to suit our Construction Site Light Location Problem (CSLLP), are set covering location models, where the objective is to minimise the cost of meeting all demand through the servicing facilities [31]. We therefore consider the light poles as facilities. We present a multi-objective Mixed Integer Programming (MIP) model to positon the light poles that service work zones on the construction site during night-time, while minimising both light installation costs and light obtrusiveness.

The remainder of this paper is organised as follows. In section 2 we present the framework applied to solve the CSLLP. We describe the steps undertaken to compute the parameters of the model in a pre-processing phase, before introducing the objective functions and the constraints associated with our proposed model in Section 3. In section 4 we test our model on a case example and report the generated results. Finally, a conclusion is presented to summarise the major work contributions.

2 Framework

In this section of the paper, we explain the overall framework, depicted in **Figure 1**, for optimising the location of the light poles around the construction site.

As an initial step the site undergoes a pre-processing phase where work zones that require lighting are delineated as rectangular boxes. Next, we identify potential locations for the light poles on and around the construction site, based on the number and positioning of work zone areas. The demand for each work zone is next specified. Potential light pole locations are identified through their vertical and azimuth angles, $\boldsymbol{B}$ and $\boldsymbol{\beta}$, respectively, measured with respect to the work zones and light sensitive receivers. The average horizontal maintained illuminance values at each of the work zones are computed to assess demand requirements, while vertical illuminance at each receiver, due to assumed light poles at each location, are used to assess the light obtrusiveness. The derived parameters are embedded in the optimisation model and a solution outlining the locations of the light poles is then obtained.

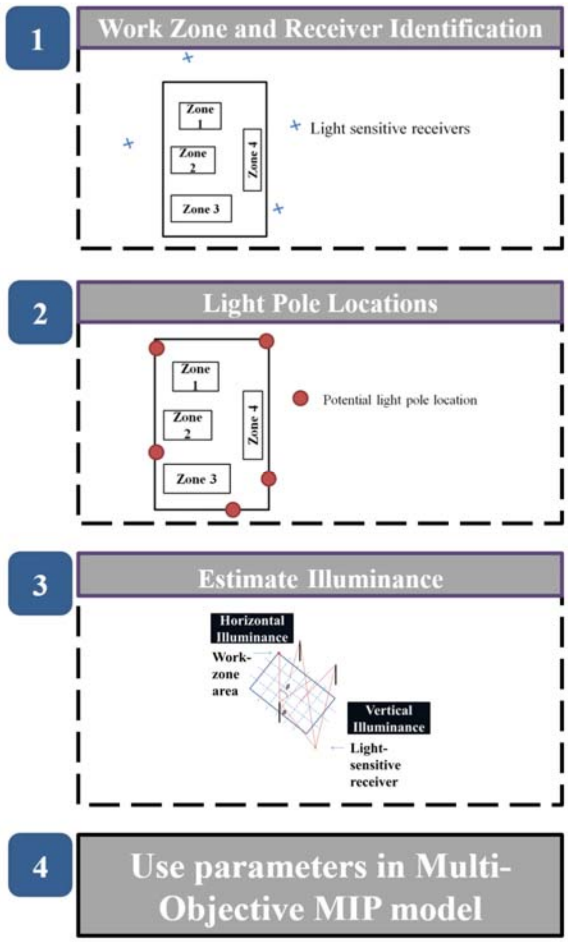

Figure 1. Framework of construction light location problem

2.1 Work zone and receiver identification

A work zone is defined as a rectangular area occupying places on the construction site where tasks are expected to be executed during night time. The reason for having to delineate the zones is to be able to discretise the overall space on a construction site, ensuring that the illuminance requirements of each relevant section of site are met. The area around the construction site needs to be surveyed to identify any light sensitive facilities, including residential dwellings, schools, etc. This then allows the planner to assess the impacts of obtrusive lights at these points, thus enabling prompt changes to the light plan to be adopted whenever needed. Lighting requirements for work zones are enacted in the form of constraints in the model that we propose.

2.2 Locating light poles

A location can only be specified if it is viable to mount a light pole on it. The location of light poles is modelled as a discrete problem and thus the potential locations appropriate for positioning the light poles need to be determined a priori. Locations should be chosen based on installation suitability, proximity to lighting area and distance away from sensitive receivers or nearby streets/roads [32], since all these factors affect the cost of light pole installations and its resulting light pollution levels.

2.3 Light parameter calculations

At the pre-processing phase, two main factors are computed for each of the potential light pole locations considered. The first of the factors, namely the horizontal maintained illuminance, E_{wl}^{H}, is used to assess the proportion of demand at work zone w that is met by the respective light pole at location l. The second factor is the vertical light illuminance, E_{rl}^{v}, used to assess impacts of light obtrusiveness on light sensitive receivers, r, in the vicinity of light installations at location l. We next detail how each of these factors is calculated

2.3.1 Illumination at work zones

To determine E_{wl}^{H} the lumen method is adopted [30]. Let ρ be the total lumen output from all luminaires within a single light pole. Let δ be the maintenance factor of the luminaires, which is dependent on the total months in use of the lamp, its burning hours and cleanliness of outdoor environment in which luminaires will be operating. Let α be the atmospheric loss factor, which varies depending on geographic location and on weather conditions. Let υ_l be the proportion of lamp flux reaching a specific area, also known as the utilisation factor, due to a pole at location l. Finally, let A_w be the total site area of work zone w that is to be lit. **Equation 1** is used to estimate the value of the average horizontal maintained illuminance at a given work zone w due to a light pole at location l.

$$E_{wl}^{H} = \frac{\rho\delta\alpha\upsilon_l}{A_w} \qquad (1)$$

To compute δ various lamp depreciation and surviving curves supplied by the luminaire manufacturers can be used [33]. For the purpose of our study we will assume that $\alpha = 1$ (i.e. no allowance for atmospheric loss is made). Calculations of υ_l are made based on the use of flux diagrams, reflecting the photometric characteristics of the considered luminaire, as will be described next.

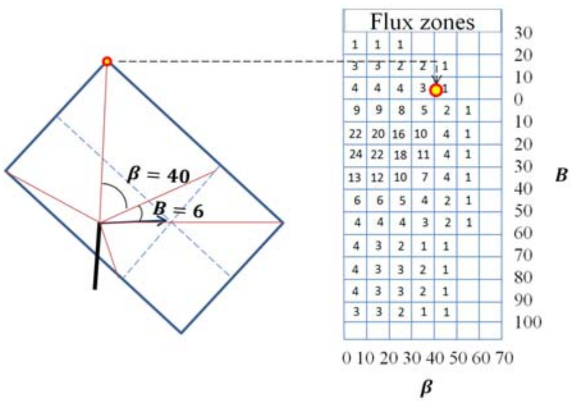

Figure 2. Plotting points of interest on the zonal flux diagram

2.3.1.1 Calculating Utilisation factor

To estimate the proportion of bare lamp flux from a light pole reaching a given area, we need to calculate the utilisation factor, using the zonal flux diagram, depicted in **Figure 2**. The zonal flux diagram, which can be obtained from the manufacturer of the luminaire under concern, corresponds to a coordinate system composed of two angles; the vertical and azimuth angles for the luminaires, expressed as $\boldsymbol{B}$ and $\boldsymbol{\beta}$, respectively. We assume that the total lumen output of each light pole is given (hence we do not worry about the number of luminaires in each pole). We also assume for simplification that all light poles are identical, having fixed heights and with the peak intensity aimed at $\frac{2}{3}$ the width of the zone. The area being considered is divided, based on the aiming angle direction, into several panels; extreme points within each panel are plotted on the zonal flux diagrams. At each point we interpolate the flux emitted per 1000 lamp lumens, from a single potential pole location, making use the zonal flux diagram. Once all grid points resulting from the aiming direction of the pole are plotted, a summation of the flux values covered by the boundary drawn through the points on the flux diagram ensues. We are then able to calculate the utilisation factor corresponding to each light pole location. A single illustrative example of plotting the relevant angles on the zonal flux diagrams is highlighted in **Figure 2**.

2.3.2 Light intensity at light-sensitive receivers

For assessments carried out at light sensitive receivers, the vertical illuminance is computed. The point at which the intensity is calculated is usually chosen as the centroid of the body representing the receiving end. Light sensitive receivers mainly represent the window of a dwelling in the close vicinity of the site. **Equation (2)** is defined to compute the vertical illuminance, E_{rl}^{V}, at receiver r, due to a pole located at location l. Light intensity emitted from a source, I_{rl}, is assessed based on the angle coordinate system defined earlier, and these are plotted on an isocandela diagram. The angle between the normal to the surface of receiver r and the direction of the light emitted from the source is represented by the symbol θ_{rl}, while the distance between the light pole location and the receiver is given by d_{rl}. The rest of the symbols of **Equation (2)** have been defined earlier on.

$$E_{rl}^{V} = \frac{I_{rl}\cos\theta_{rl}}{1000{d_{rl}}^{2}}\rho\delta\alpha \qquad (2)$$

3 Light pole location optimisation models

In this section, we present the multi-objective light pole location model, comprising of the objective functions and the set of constraints. One of the objective functions serves to minimise the maximum obtrusive effect of light, as measured at all light sensitive receivers in the vicinity of the constructions site. The second objective function is defined to minimise the cost of installing the light poles around the construction site. Constraints define the feasible search region; they are mainly specified to ensure full light coverage at all work zone areas. It is assumed that illuminance on a point is additive. Each objective function and the associated constraints of the model are described next. The notation adopted for the optimisation model is given in **Table 1**.

Table 1 Notation of sets, parameters and variables

Notation	Definition

Sets	W	Set of work zones, indexed by w
	L	Set of light pole locations, indexed by l
	R	Set of light-sensitive receivers, indexed by r
Parameters	D_w	Illuminance required at each work zone w
	E_{wl}^{H}	Average horizontal illuminance delivered to work zone w by a light pole positioned at l
	E_{rl}^{V}	Vertical illuminance delivered by a light pole positioned at l to receiver r
	c_l	Cost of installing a light pole at location l
	P	Maximum number of light poles that can be installed
Variables	x_l	Binary variable indicating whether a light pole is positioned at location l or not

3.1 Objective functions

The construction light location problem is modelled as a multi-objective MIP, where two objective functions are defined. Both objective functions warrant a sustainable implementation of a light plan, through targeting social, environmental and economic aspects.

3.1.1 Minimising Obtrusive effect of Light

The first objective function, defined in **Equation (3),** aims to minimise the maximum vertical illuminance experienced at any of the receivers near the construction area. **Equation (3)** thus acts as a social/environmental cost function that aims to reduce the obtrusiveness of the light plan adopted.

$$\text{Minimise} \quad \max_{r\in R}\left\{\sum_{l\in L} E_{rl}^{V} x_l\right\} \tag{3}$$

3.1.2 Minimising Light pole installation costs

A second objective function, Equation (**4**) is incorporated into CSLLP, which targets the minimisation of the light pole installation costs. The location variable x_l controls the number of poles to be positioned within the construction site. Minimising this number will lead to cost savings. In addition, embedded in the equation is the cost parameter, which varies depending on the location of installation and any associated requirements needed for preparing that specific location for light pole fixing.

$$\text{Minimise} \quad \sum_{l\in L} c_l x_l \tag{4}$$

3.2 Constraints

Several hard constraints are defined to delineate the feasible search region based on criteria such as demand coverage, along with specifying the domain of the involved variables. The section below describes each formulated constraint.

3.2.1 Satisfying demand at work zones

An assessment of the average horizontal illuminance is carried out at each work zone, whenever a pole is chosen to be located at one of the given discrete locations. **Equation (5)** is specified to warrant full light coverage of each work zone, as is determined by illumination levels from all locations $l \in L$ that cover D_w.

$$\sum_{l\in L} E_{wl}^{H} x_l \geq D_w \qquad \forall w \in W \tag{5}$$

3.2.2 Number of light poles

When full coverage of an area is required, a natural tendency of the optimisation algorithm would be to associate as much light poles as is permitted, subject to the objective functions. In practice a limit is naturally enforced on the number of facilities that provide a service due to limited resource availability. As such, we define **Equation (6)** to limit the total number of permitted light poles to be positioned on the construction site.

$$\sum_{l} x_l \leq P \tag{6}$$

3.2.3 Variable Domain

A single group of variables is present in the proposed model, namely the location variable x_l . We require the variable to be binary; hence, Equation (7) is defined.

$$x_l \in \{0,1\} \qquad \forall l \in L \tag{7}$$

3.3 ε - constraint Method

For solving the multi-objective CSLLP, we adopt the ε - constraint method. This entails the re-formulation of the model to adhere to the format shown in **Equation (8)**, where $\mathbf{y}$ refers to the vectors of decision variables while Y denotes the feasible set. As a first step, both objective functions are optimised individually to obtain the extreme points of the Pareto frontier. Once the optimal values for both functions have been derived the model is formulated in such a manner that a single objective function is considered whilst the other function is incorporated as a constraint [34]. Initially, the objective function chosen as the constraint, $f_2(\mathbf{y})$, is upper bounded by its respective optimal solution, z_2^*. This requirement is slowly relaxed as the optimisation proceeds, through incrementing ε, until the constraint becomes no longer binding.

$$\begin{aligned} &\text{Minimise } f_1(\mathbf{y}) \\ &\text{such that} \\ &f_2(\mathbf{y}) < z_2^*(1+\varepsilon) \\ &g_u(\mathbf{y}) \le 0 \quad \forall u = 1,..,k \\ &\mathbf{y} \in Y \end{aligned} \tag{8}$$

4 Case Example

To highlight the applications of our proposed model, we implement the developed multi-objective MIP formulations on an illustrative case project to solve the CSLLP. The project, depicted in the plan view of **Figure 3**, relates to the construction of a railway line along the outskirts of an urban city. The project is split into various stages and our analysis is conducted over a single stage, namely the installation of concrete sleepers along the rail alignment.

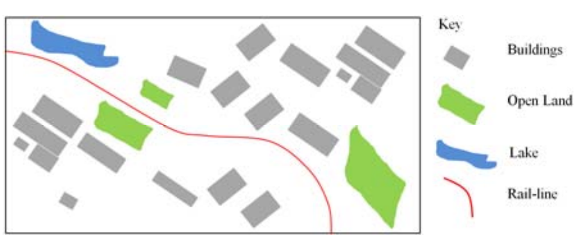

Figure 3. Plan view of rail line construction project

For installing the sleepers, it is required that work be conducted over a duration of two months, with several periods extending into the night time hours. Illuminance is measured at two main light sensitive receivers, namely residential dwellings and a nearby age care facility. The aim is then to provide a suitable light plan to account for the night work light requirements, while at the same time ensuring that light obtrusiveness at the receivers is kept to a minimal. We assume that 11 potential locations for installing the light poles, all satisfying electrical requirements etc., have been identified a priori, and these are shown by the red circles on **Figure 4**.

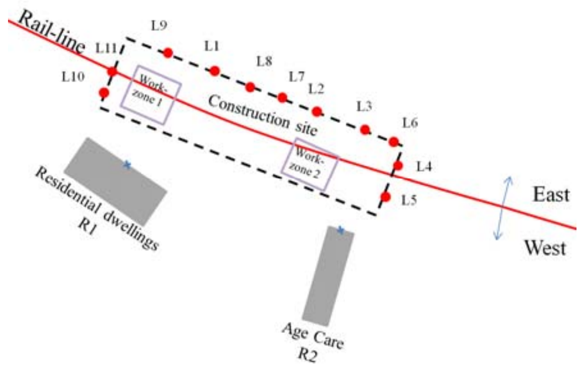

Figure 4. Construction site layout and proposed locations of floodlights

Two work zones are also delineated; area of work zone 1 is 12,000 m^2 while that of work zone 2 is 13,200 m^2. It is specified that for both work zones an average illuminance of 170 lx is required. The light luminaires to be installed are mounted 2000 W metal halide floodlights, beam type B, mounted at a height of 14 m, with 310,000 lumens of output. The associated zonal flux diagram is obtained from the manufacturer. All floodlights, once mounted, are assumed to have a fixed aiming angle of 62°. The calculation of the average horizontal illuminance, based on a grid point system as described earlier in the paper, was performed, and the results obtained for each potential location are reported in **Table 2**. Also, the vertical illuminance was calculated at the two receivers, the residential dwellings and the age care facility, shown in **Figure 4**. These parameters were then input into the model of **Equations (3) – Equation (7)**. Maximum number of light poles that can be installed was set to 8. The ε - constraint method was adopted for solving the proposed model, where the light obtrusiveness objective function was formulated as a constraint, while the light cost installation function was minimised. CPLEX was used as the linear solver to obtain the optimum solutions [35].

Table 2 also gives the cost of placing a floodlight at the discrete positions identified. The costs take into account the necessary electrical setup and site preparation required for installing the mounting poles. It is noticed from the cost figures of **Table 2** that the light pole locations on the eastern side of the line happen to have a higher cost than ones located on the western side. This has been attributed to differences in the topography of the land. The Pareto front of the optimisation problem is displayed in **Figure 5**, where the conflicting nature of the objective functions, for the particular project we consider, is apparent. Results highlight that having a low cost light plan configuration, at $ 27,289 would imply a high obtrusive light lux, measured at 118.76 lx, at one of the receivers. The opposite is true when a solution that minimises the light obtrusiveness is sought; this time the lowest of the maximum resulting light illuminance at a receiver is measured at 69.73 lx, with an associated light plan cost of $34,470. High costs are related to the locations chosen for positioning of the floodlights, as noted on the Pareto front of **Figure 5**.

Table 2 Model Parameters

Location	Work zone illuminance 1	Work zone illuminance 2	E_{wl}^{V} R1	E_{wl}^{V} R2	Cost (AUD)
L1	28.52	9.07	20.10	15.34	4903
L2	12.83	50.56	10.68	27.16	4785
L3	7.84	38.89	5.80	31.61	4941
L4	6.42	13.61	0.22	84.12	2478
L5	6.42	14.91	0.12	155.99	452
L6	7.13	25.28	3.31	32.01	5214
L7	14.26	25.93	12.81	22.11	4850
L8	17.11	12.32	14.81	18.28	5208
L9	47.77	7.78	25.04	12.89	5070
L10	57.75	5.83	49.85	0.29	369
L11	62.03	6.48	46.03	0.33	4200

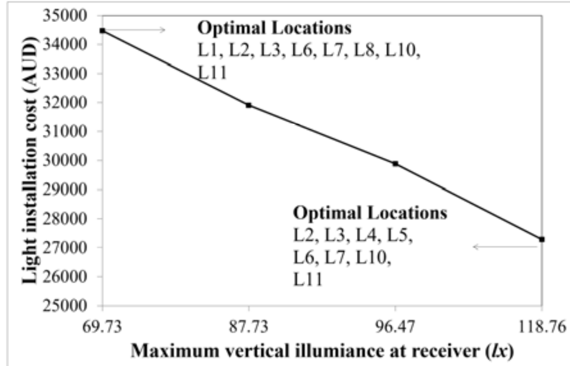

Figure 5. Pareto front highlighting efficient solutions to the multi-objective model

5 Conclusion

A multi-objective location set covering MIP was presented to solve the construction site light layout problem. The model involved two main objective functions; the first objective function minimised light obtrusiveness while the second function minimised light pole installation costs. Constraints were formulated to ensure full coverage of work zones on the construction site. In order to derive the Pareto front, the ε-constraint method was adopted, where globally optimal solutions were incrementally obtained. For the case study on which the model was applied, both objective functions happened to conflict, resulting in an efficient Pareto frontier. The results presented in this work highlight the potential for reducing light pollution through light location optimisation. Further work will focus on modelling the physics of cumulative light coverage at a point more precisely.

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