



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
15.05.2024 Bulletin 2024/20

(51) International Patent Classification (IPC):
H05B 47/105 (2020.01) **H05B 47/115** (2020.01)
H05B 47/19 (2020.01) **G05B 17/02** (2006.01)

(21) Application number: **22020553.8**

(52) Cooperative Patent Classification (CPC):
H05B 47/19; H05B 47/105; H05B 47/115

(22) Date of filing: **14.11.2022**

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
KH MA MD TN

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(54) **A CENTRALIZED MODEL PREDICTIVE LIGHTING CONTROL METHOD AND A CENTRALIZED PREDICTION-BASED CONTROLLABLE STREET LIGHTING SYSTEM**

(57) The present invention relates to a centralized model predictive lighting control method for one or more streetlamps and a system thereof, particularly to creating a lighting, which dynamically adjusts a light intensity thus improving a comfort level of visibility for vehicles, pedestrians, cyclist, etc., in variable weather conditions, while minimizing an energy consumption of a system simultaneously. The method predicts the light intensity at a pre-determined set of points of interest p in a space over a prediction horizon N with a time resolution of T_s and ad-

justs the light intensity of the streetlights according a pre-determined streetlight dimming scenario and by implementing a Model Predictive Control (MPC) algorithm configured to control light intensities of one or more streetlamps. The MPC algorithm performs minimizing an objective function over the prediction horizon N with the time resolution of T_s , the objective function comprising calculating light intensity, light pollution, and deviation from the desired lighting at the predetermined set of points of interest p considering calculated constraints.

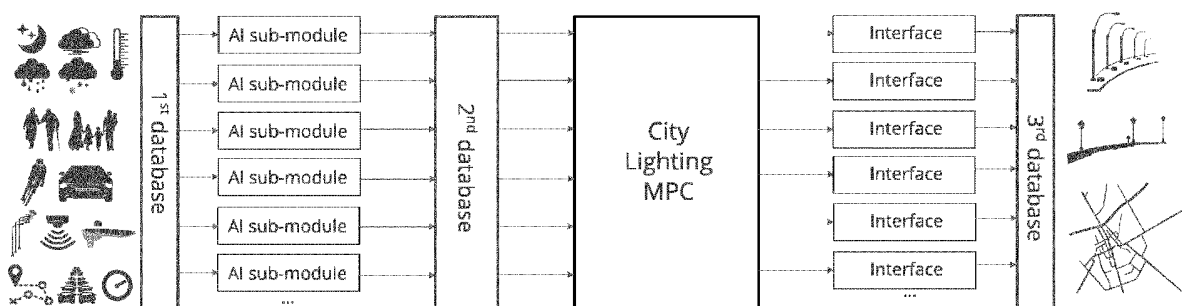


Fig. 7

Description

[0001] The present invention proposes an optimal centralized model predictive lighting control method for one or more streetlamps to dynamically adjust a light intensity of streetlamps for improving a comfort level of visibility for vehicles, pedestrians, cyclist, etc., in variable weather conditions, while minimizing an energy consumption of a system simultaneously. The present invention also relates to a centralized prediction-based controllable street lighting system.

BACKGROUND ART

[0002] One of the most significant documents on the energy efficiency of lights in patent literature is EP2719258. This document proposes to modify the parameters of public lighting through current or expected weather data. This system is interesting but it does not take into consideration the current methods of lighting systems and does not appear to be of real assistance in actual energy saving, which should likewise be based on the intensity of use of the area. Current lighting technology design criteria provide a first sizing of the lighting based on the geometry of the areas to be lit, whereby measuring parameters are taken into consideration, such as the length or width of the roads, etc. Further, it is desirable for the design to take into consideration actual traffic variables, dimming, pedestrian and weather data and road conditions.

[0003] A further document in the field is US2019/0008019, which describes a system for controlling the intensity of public lighting based on the perception and processing of images. US2019/0008019 aims at a minimal communication system between lighting points. In particular, the lighting points change light intensity when a movement is perceived in the visual field or a change in intensity of a nearby streetlamp is perceived. In this way, the streetlamps communicate with the ones nearby without the need for a complex system. This system allows keeping the lighting at a low level when it is not required, but it does not allow lowering the lighting technology classes initially assigned to the project because it does not allow having traffic data, dimming, pedestrian and weather data and road conditions.

[0004] Said system also has other disadvantages, in particular the cameras are costly, they have a limited sensing radius whereby there are to be several of them, and they can be tricked if there are shields in the visual field such as, for example trees that change their foliage seasonally or road signage.

[0005] US2019/0008019 also suggests a hybrid between the visual and sound solution in which the streetlamps initially are turned OFF, and where the sound sensing is only used to turn them ON and make the visual system operational. Then, the decision is made to adjust or turn OFF the lighting unit, if other nearby sources already provide the scene with enough light.

[0006] A more complex system, in particular both adaptive and predictive, is described in US2016/0050397. This system is adaptive because it aims to declassify lighting technology and is predictive because it adjusts the light flow based on instant predictions of events. To achieve these goals, the system of US2016/0050397 makes use of a visual perception artificial intelligence, i.e., taught to learn and classify traffic data based on images. In general, this system is very costly due to the main component required, that is the cameras. Moreover, its instant prediction ability and reactivity based on images alone are limited because while the cameras are arranged in an appropriate manner, the vision of the action field might not be optimal due to obstacles or orientations that provide overlapping of the vehicles. Moreover, as is known, images are projections of light that bounces off objects and travels in a straight line alone, thereby it is not possible to perceive images from behind a crossroad or traffic sign or tree with one camera alone, therefore it is not possible to predict, for example the turns of the vehicles. To obviate this drawback, the number of cameras should be high, but this obviously would increase the costs.

[0007] The object of the present invention is to overcome all or some of the drawbacks of the known techniques.

SUMMARY OF THE INVENTION

[0008] The main objective of a centralized model predictive lighting control method and system thereof is to provide an optimal utilization of the installed streetlights by adjusting their light intensities (brightness) considering the surrounding conditions. Such adjustment should, simultaneously, minimize an energy consumption of the control system and maintain a desired level of comfort visibility for vehicles, pedestrians, cyclists, etc. The method predicts a light intensity on a street surface over a prediction horizon N with a time resolution of T_s and adjusts the luminous intensity of the streetlights according to it through an optimal solution of the energy efficiency and the comfort level of visibility.

[0009] In particular, it is the general object of the present invention to increase an energy saving in the field of street lighting system on an existing structure, without increasing significantly the costs.

[0010] It is a further general object of the present invention to provide a centralized method and a centralized street lighting system that is predictive and adaptive.

[0011] The object is solved by the subject matter of the independent claims. Further embodiments are shown by the dependent claims.

[0012] A basic idea of the invention is to implement: a modelling method and generating prediction data for a prediction

horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions at a predetermined set of points of interest p , the prediction data are generated comparing a respective historical weather, traffic, pedestrian and road data and the latest weather, pedestrian, traffic, and road condition data; a spatial coordination-based model of light propagation at the predetermined set of points of interest p ; and generating a predetermined streetlight dimming scenario at the predetermined set of points of interest p for one or more streetlamps for delivering a desired amount of light intensity over the prediction horizon N with the time resolution of T_s , the predetermined streetlight dimming scenario is based on a generated prediction data; and a Model Predictive Control (MPC) algorithm configured to calculate light intensities of one or more streetlamps according to a dynamic reference values, assigned weighting coefficients determining a significance of each point of interest p and spatial coordination-based model at the predetermined set of points of interest p , the Model Predictive Control (MPC) algorithm performs calculating a sequence of the control actions over the prediction horizon N with the time resolution of T_s for the one or more street lamps and provides control actions to control devices of the one or more street lamps to change an applied voltage, power or current. According to the embodiment of the invention a dynamic reference values are selected according to the predetermined streetlight dimming scenario, wherein an assigned variables and thresholds includes precipitation level, visibility data, traffic density, diversity and density of pedestrians.

[0013] According to the embodiment of the invention a Model Predictive Control (MPC) algorithm performs minimizing an objective function over the prediction horizon N with the time resolution of T_s , the objective function comprising calculating light intensity, light pollution, and a deviation from the desired lighting at a predetermined set of points of interest p considering generated predetermined streetlight dimming scenario at the predetermined set of points of interest p ; technical specifications of each streetlamp; and calculated constraints for: street lighting norms requiring the least amount of light at the predetermined set of points of interest p at a street surface, a spatial coordination-based model of light propagation at the predetermined set of points of interest p , and lighting transition dynamics limitations of streetlamps.

[0014] Further, the invention provides implementing a spatial coordination-based model being a weather-dependent spatial physical model of light propagation in a space at a predetermined set of points of interest p , where a propagation of light considering weather conditions (vu) can be uniformly generalized.

[0015] Also described is a centralized prediction-based controllable street lighting system configured for implementing a centralized light-based model predictive control method for one or more streetlamps.

[0016] Also provided is a computer program comprising program code that, when executed by a processor, enables the processor to carry out a centralized light-based model predictive control method for one or more streetlamps.

[0017] Further provided is a record carrier storing a computer program according to the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Further characteristics and advantages of the present invention will become clearer from the following detailed description of the preferred embodiments thereof, with reference to the appended drawings and provided by way of indicative and non-limiting example, wherein:

Fig. 1 illustrates a steady-state illuminance intensity distribution, without considering weather and glare effects, at any point of interest p on a street surface;

Fig. 2 illustrates an example of observed points of interest A-K;

Fig. 3 illustrates an example of a propagation of city lighting;

Fig. 4 is a schematic illustration of a streetlight luminaire;

Fig. 5 are graphs illustrating model predictive control-based optimization results with gradual transitions, performed on a street segment of four lamps and six points of interests, where a priority is set to Points A and B, then on another points D, E, C, and G, respectively;

Fig. 6 illustrates an example flowchart for a centralized model predictive lighting control method for one or more streetlamps; and

Fig. 7 is a schematic illustration of a centralized prediction-based controllable street lighting system according to aspects of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0019] A centralized model predictive lighting control method for one or more streetlamps controlling the illuminance intensities of the streetlight lamps considering weather conditions and vehicles and pedestrian movements is the main objective of the present invention. Such control method improves an energy efficiency (optimal utilization) of a centralized prediction-based controllable street lighting system while maintaining comfortable level of brightness for safety and security reasons.

[0020] The centralized model predictive lighting control method is based on convex optimization and linear or quadratic program with constraints and combines developed dynamic mathematical models of lighting, lighting requirements, models of location conditions and tariff conditions of electricity billing, with the common goal of minimizing labour and maintenance costs. The control method takes place in a real time for the calculation of the corresponding control actions of individual lighting poles (lamps) and an entire lighting system for individual locations.

[0021] In the following, an embodiment of the centralized model predictive lighting control method is described and illustrated in a flowchart, Fig. 6. The method for the centralized prediction-based controllable lighting system for one or more street lamps comprises providing a centralized prediction-based controllable lighting system for one or more street lamps, the system comprising software systems and protocols, connectivity and telemetry exchange modules to and between a control device of each streetlamp and a central computer or computer cloud, wherein each lamp light intensity is activated by a control action. Said software systems may be aided by suitable protocols which act as distributed control means, standards, frameworks, and mechanisms for self-regulating large volumes of distributed entities to achieve a collective objective or benefit. Said connectivity means typically include standard communication technologies such as fixed and wireless telephony and mobile networks (GPRS, 1-5G, LTE), local communication technologies such as WiFi, Z-Wave, Zigbee, mesh networks, Powerline or signals carried over an electrical circuit, together with leverage of the Internet and remote computers, and cloud hosted components and technologies, and on end customer devices. The method comprises setting of a prediction horizon N , time resolution T_s , number of lamps, number of a predetermined set points of interest p for one or more street lamps and weighting coefficients determining a significance of each point of interest p . The method further comprises obtaining of historical weather, traffic, pedestrian and road condition data and a latest weather, pedestrian, traffic, and road condition data. The latest weather, pedestrian, traffic, and road condition data are being continuously saved and used for updating the historical weather, traffic, pedestrian and road data. The historical weather, traffic, pedestrian and road data have been collected and processed at least for a three-month period to establish different occurrences. The latest weather and road condition data can be obtained from onsite measurements of meteorological sensors or remote sources on meteorological information and combinations thereof; pedestrian data can be obtained from pedestrian mobile phones, wearable devices, traffic counters, video and acoustic sensors, or from remote sources on traffic information and combinations thereof; and the latest traffic data are obtained from onsite measurements of traffic counters, video and acoustic sensors, and from remote sources on traffic information, and combinations thereof.

[0022] Further, the method comprises generating prediction data for a prediction horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions at the predetermined set of points of interest p , the prediction data are generated comparing a respective historical weather, traffic, pedestrian and road data and the latest weather, pedestrian, traffic, and road condition data. Each generated prediction data is implemented by a modelling method by one of the groups consisting of physical models, machine learning methods, or neural networks. The method further comprises calculating a spatial coordination-based model of light propagation at the predetermined set of points of interest p and generating a predetermined streetlight dimming scenario at the predetermined set of points of interest p for one or more streetlamps for delivering a desired amount of light intensity over the prediction horizon N with the time resolution of T_s , the predetermined streetlight dimming scenario is based on the generated prediction data. The spatial coordination-based model includes calculated light intensities in the predetermined set of points of interest p based on a steady-state light intensity distribution and a continuous, gradual transition between two levels of light intensities over two-time intervals with an arbitrary rate of change. The method further comprises selecting dynamic reference values for the predetermined set of points of interest p over the prediction horizon N with the time resolution of T_s , the dynamic reference values are selected according to the predetermined streetlight dimming scenario and implementing a Model Predictive Control (MPC) algorithm. The Model Predictive Control (MPC) algorithm is configured to calculate light intensities of one or more streetlamps considering the dynamic reference values, assigned weighting coefficients and calculated spatial coordination-based model at the predetermined set of points of interest p , the Model Predictive Control (MPC) algorithm performs calculating a sequence of the control actions over the prediction horizon N with the time resolution of T_s for the one or more street lamps and provides control actions to control devices of the one or more street lamps to change an applied voltage, power or current.

[0023] According to embodiment of the present invention, generating the predetermined streetlight dimming scenario is based on scenario conditions, the scenario conditions are depending on a day light duration, weather, traffic and pedestrian conditions, wherein the each of said conditions has an assigned variable and threshold used for selecting

the dynamic reference values. Further, the predetermined streetlight dimming scenario is continuously and real-time updated over the prediction horizon N with the time resolution of T_s .

[0024] A prediction of the light intensities at each of the predetermined set of points of interest p is based on the dynamic reference values, weighting coefficients and the spatial coordination-based model, the spatial coordination-based model is a function of light intensities reaching the predetermined set of points of interest p from one or more streetlamps considering a distribution of the light intensities in a space in different weather conditions and taking into account reflections from all light sources.

[0025] Weather phenomena examined to establish different scenario conditions being Temperature, Precipitation, Visibility and Humidity. Precipitation is any product of the condensation of atmospheric water vapor that falls on the ground. It can be divided in 2 categories - liquid precipitation (rain) and solid precipitation (snow). The weather phenomena highly related to precipitation is humidity. That is the amount of water vapor in the air, expressed in %. In meteorology, by definition visibility is the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background, or the greatest distance at which lights of 1,000 candelas can be seen and identified against an unlit background. Weather conditions used for the scenarios are: clear, dry weather; rain; snow and ice, and fog. Clear, dry weather is characterized by high visibility and no precipitation.

[0026] According to the historical traffic and weather data, street lighting norms, together with empirical aspect of city users and street lighting technology provider, available scenario conditions are determined. Table I below comprises a list of examples of the scenario conditions with a characteristic of each.

Table I. EXAMPLES OF THE SCENARIO CONDITIONS

Scenario				Conditions	
	Year period	Weather conditions	Traffic	Characteristics	Variables and Thresholds
1	Summer	Clear, dry	Light or no traffic	Short night	Lighting duration < 10h
				Normal operation	Precipitation = 0 Visibility ≥ 10 km
				Energy saving mode	Traffic density < 4
2	Summer	Clear, dry	Moderate	Short night	Lighting duration < 10h
				Normal operation	Precipitation = 0 Visibility ≥ 10 km
				Mid illumination requirements	4 $\leq$ Traffic density < 8
3	Transitional (spring/autumn)	Clear, dry	Severe	Balanced day-night periods	Lighting duration ~ 12 h
				Benchmark lighting, normal operation	Precipitation = 0, Visibility ≥ 10 km
				High illumination requirements	8 $\leq$ Traffic density < 10
4	Transitional (spring/autumn)	Rain	Moderate	Balanced day-night periods	Lighting duration ~ 12 h
				Increased glare, sudden changes	Precipitation > 0, Humidity > 90% Visibility ≤ 10 km
				Mid illumination requirements	4 $\leq$ Traffic density < 8
5	Winter	Rain	Moderate	Long night	Lighting duration > 14h
				Increased glare, sudden changes	Precipitation > 0, Humidity > 90% Visibility ≤ 10 km
				Mid illumination requirements	4 $\leq$ Traffic density < 8

(continued)

Scenario				Conditions	
	Year period	Weather conditions	Traffic	Characteristics	Variables and Thresholds
6	Winter	Snow and ice	Light	Long night	Lighting duration >14h
				Increased glare, critical safety	Temperature $\leq 0^{\circ}\text{C}$, Precipitation > 0 Humidity > 90% Visibility ≤ 10 km
				Energy saving mode	Traffic density < 4
7	Winter	Fog	Moderate	Long night	Lighting duration >14h
				Reduced visibility, increased reflection	Precipitation = 0 Humidity > 90% Visibility < 10 km
				Mid illumination requirements	4 $\leq$ Traffic density < 8

[0027] The scenario conditions are depending on a year period lighting duration, weather, traffic and pedestrian conditions, wherein the year period lighting duration and each of said conditions has an assigned variable and threshold used for selecting dynamic reference values. The assigned variables and thresholds include precipitation level, visibility data, traffic density, diversity and density of pedestrians.

[0028] Therefore, each scenario condition is determined by a specific traffic, pedestrian and weather conditions and as a result provides a unique predetermined streetlight dimming scenario. The list of examples of the predetermined streetlight dimming scenarios is given in a Table II below.

Scenario conditions				Dimming profile or predetermined streetlight dimming scenario	
	Weather conditions	Traffic conditions Pedestrian conditions	Dynamic reference Variables and Thresholds		
5	1	Clear, dry	Light or no traffic and Small pedestrian percentage	precipitation = 0 visibility $\geq 10\ 000$ traffic density < 4 pedestrians_total < 10.0	D1 0.5@90% 0.5@40%
10					
15					
20					
25	2	Clear, dry	Moderate traffic or Moderate pedestrian percentage	precipitation = 0 visibility $\geq 10\ 000$ traffic density ≥ 4 traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	D2 0.5@95% 0.5@55%
30	3	Clear, dry	Severe traffic or Severe pedestrian percentage	precipitation = 0 visibility $\geq 10\ 000$ traffic density > 8 pedestrians_total > 50.0	D3 0.7@100% 0.3@75%
35	4	Rain	Moderate traffic or Moderate pedestrian percentage	precipitation > 0 humidity ≥ 90 visibility $\leq 10\ 000$ traffic density ≥ 4 traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	D4 0.5@100% 0.5@75%
40	5	Snow	Moderate traffic or Moderate pedestrian percentage	precipitation > 0 humidity ≥ 90 temperature < 0 visibility $\leq 10\ 000$ traffic density ≥ 4 traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	D5 0.5@80% 0.5@50%
45	6	Fog	Moderate traffic or Moderate pedestrian percentage	precipitation > 0 humidity ≥ 90 temperature ≤ 4 visibility $\leq 10\ 000$ traffic density ≥ 4 traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	D6 0.5@90% 0.5@50%
50					
55					

Table II. PREDETERMINED STREETLIGHT DIMMING SCENARIOS

[0029] For instance, the predetermined streetlight dimming scenario (i.e., Dimming profile) provides the information on luminaire power consumption during operation. The dimming profile of e.g., 0.3@100% and 0.7@75% means that the luminaire is using 100% of rated power for 30% of an operation time, and for the remaining 70% operation time it is operating on 75% rated power. Duration of operation of 100% depends on the day duration for the considered location. It is adjustable over year and is defined by the lighting norms or city users.

[0030] The Model Predictive Control (MPC) algorithm performs minimizing an objective function over the prediction horizon N with the time resolution of T_s , the objective function comprising calculating light intensity J_{en} , light pollution J_z , glare, and a deviation $J_{A...K}$ from the desired lighting at the predetermined set of points of interest p considering:

- a- calculated constraint for street lighting norms requiring the least amount of light on specifically defined point(s) on the road;
- b- generated predetermined streetlight dimming scenario determined by the desired light intensity and a weighting coefficient that determines a significance of each point of interest p ;
- c- calculated constraint for the spatial coordination-based model of light propagation at the predetermined set of points of interest p ;
- d- calculated constraint for lighting transition dynamics limitations of the streetlamps; and
- e- technical specifications of the one or more streetlamps.

[0031] In the following, the objective function is described.

[0032] Lighting lamps provide a necessary lighting and are dimensioned according to clear weather conditions, and according to the given international lighting standards. Lamp design, LED quality and their configuration (network) and lens / diffuser, as well as power electronics, diversify manufacturers, quality and efficiency. The norms define a required quality of lighting, mainly depending on the class of the road and not more precisely than that. Recently, the notion of a level of vertical lighting is often mentioned, i.e., the perception of lighting from the perspective of people (drivers, pedestrians and cyclists), but this part is not yet included in the norms but represents a future path. Fig. 3 gives an illustrative example of a designing city lighting where it is evident that a surface (e.g., road) lighting is placed in the foreground and often the only plan.

[0033] Light propagates according to a well-known physical law and it is possible to express a dependence of a point in space depending on an angle and distance from a light source. As there are more lamps, reflection from the substrate and surrounding objects, i.e., more light sources, the light intensity of a particular point in space is the sum of all these sources and can be described by an exact mathematical law.

[0034] The total illumination at an arbitrary point in space where n different sources contribute can be described by:

$$E(x, y, z) = \sum_{i=1}^n E_i(x_i, y_i, z_i) = \sum_{i=1}^n f_i(I_i, l, \gamma), \quad (1)$$

where x, y, z are the coordinates in space, and where the contribution of each individual component is defined by the strength of source I , distance l and spatial variables (column height, lamp inclination, spatial angles of the observed point relative to the source, etc.) that are combined represented by the parameter γ .

$$E(x, y, z) = f(I, l, \gamma). \quad (2)$$

[0035] In different weather conditions, primarily rain and fog, additional phenomena occur. In fog, the intensity of illumination decreases further due to the distance from the source and the density of fog, but there is a pronounced vertical component of illumination, i.e., glare caused by light scattering on fog particles, where each particle can be physically described as a new separate light source. An additional significant phenomenon in road traffic is the headlights of vehicles coming from the opposite direction and their behaviour in foggy conditions. To get an impression, the fog is made up of small drops of water whose radius is usually less than 100 μm . The mean radius of the droplet is usually 2-5 μm , while the density ρ of the mist is from 10^6 to 10^9 droplets per cubic meter. The liquid water content varies between 0.003 g/m³, for light fog, to 2 g/m³, for thick fog.

[0036] In the case of rain, the size of the droplets is significantly larger and their density in space is significantly lower than in the case of fog particles, and due to the rainfall, no significant vertical component is created. On the other hand, in this case, the reflection from the horizontal surface (road) is very pronounced, which significantly affects the subjective perception of the driver. In the case of snow, a slower fall causes a more pronounced scattering of light or a vertical component, and a longer fall creates a very pronounced reflection from the ground (white road).

[0037] Weather conditions can be represented through a visibility parameter, which is also available as a component of weather conditions, either current measurement or weather forecast (parameter prediction). The spatial coordination-based model refers to a weather-dependent spatial physical model of light propagation in a space at the predetermined set of points of interest p , where the propagation of light considering various weather conditions (vu) can be uniformly generalized and represented as:

$$E_{vu}(x, y, z) = E(x, y, z)e^{-3/v\tau} = f(I, l, \gamma, V), \quad (3a)$$

where V is visibility in meters, and a parameter T denotes a thickness of the fog and can also be related to the visibility parameter. Snow is additionally related to a temperature parameter.

[0038] Glare or blinding is a temporary (or permanent) disturbance in the observer's field of vision and, depending on the intensity, causes a feeling of discomfort to the point of complete visual incapacity. Glare is empirically modelled as:

$$E_g(x, y, z) = 10 E(x, y, z)(\theta_g^2 + 1.5\theta_g)^{-1} = f(I, l, \gamma), \quad (3b)$$

where E_g is the light intensity in the point of interest p that comes from the source of light or reflection, and θ_g is an angle of incidence. For $\theta_g = 0$, the source directly aimed at the observer's eyes, according to (3b), an infinite amount of reflection is actually obtained, which can be saturated to arbitrary selected maximum value. Variable z is also often set to a constant value, typically for eye height at 1.45 m.

[0039] From all the above, it follows that each point of space can be described by exact physical relations that take into account weather and glare conditions - as the sum of all different influences of sources, reflections, scattering, etc. Furthermore, any number of the predetermined set of points of interest p where we want to regulate lighting intensity can be chosen, and potentially the angle of incidence. These points can be declared as points of special interest and defined in space to correspond to the following coordinates: eye level of the average driver (left and right side of the road), eye level of the average pedestrian (left and right side of the road), ground lighting (middle of the road), visibility of the left edge of the road, visibility of the right edge of the road, and even a step further, the height of the eyes of children or adults in wheelchairs, etc. and thus, make for each lamp individually with, for example, known coordinates of one dimension (maximum illumination, i.e. just below the lamp), and further expand to one street separately, the entire city section (neighbourhood, square, etc.) with individual or combined consideration.

[0040] An example of the predetermined set of points of interest p is shown in Fig. 2 where the points are marked with letters A-K. For each of these points, an exact desired light intensity can be determined, either for all the same values corresponding to a precisely defined norm, or further corrected according to the subjective impression while the norm (e.g., ground / road illuminance) is simultaneously satisfied. Furthermore, for each point, its priority over other points (weighting coefficient) can be determined, thus giving different importance to the optimization problem that aims to simultaneously satisfy all desired levels at all points, but in a way that gives priority to the more important ones.

[0041] The dimming profile or the predetermined streetlight dimming scenario is transformed to light intensity for each chosen point of interest p , individually or in groups, determined by the desired light intensity (i.e., Reference) and weighting coefficient that determines a significance of each point of interest p , with an exemplary Table III given below:

Scenario conditions				Points of interests references	Points of interests weighting coefficients
1	Weather conditions	Traffic conditions Pedestrian conditions	Dimming profile		
	Clear, dry	Light or no traffic and Small pedestrian percentage	D1		
2	Clear, dry	Moderate traffic or Moderate pedestrian percentage	D2	A, B, C: D1; D, E, F: 0.8 D1 G, H, I: 0.6 D1 J: 0.5 D1; K: 0.8 D1	A, B, C: 0.9; D, E, F: 0.7 G, H: 0.5 I: 0.3; J: 0.2; K: 0.5
3	Clear, dry	Severe traffic or Severe pedestrian percentage	D3	A, B, C: D2; D, E, F: 0.8 D2 G, H, I: 0.6 D2 J: 0.5 D2; K: 0.8 D2	A, B, C: 1.0; D, E, F: 0.7 G, H: 0.5 I: 0.3; J: 0.2; K: 0.6
4	Rain	Moderate traffic or Moderate pedestrian percentage	D4	A, B, C: D3; D, E, F: 0.8 D3 G, H, I: 0.6 D3 J: 0.5 D3; K: 0.8 D3	A, B, C: 1.0; D, E, F: 0.8 G, H: 0.5 I: 0.4; J: 0.3; K: 0.6
5	Snow	Moderate traffic or Moderate pedestrian percentage	D5	A, B, C: D4; D, E, F: 0.8 D4 G, H, I: 0.6 D4 J: 0.5 D4; K: 0.8 D4	A, B, C: 1.0; D, E, F: 0.8 G, H: 0.6 I: 0.4; J: 0.4; K: 0.7
6	Fog	Moderate traffic or Moderate pedestrian percentage	D6	A, B, C: D5; D, E, F: 0.8 D5 G, H, I: 0.6 D5 J: 0.5 D5; K: 0.8 D5	A, B, C: 0.8; D, E, F: 0.7 G, H: 0.5 I: 0.3; J: 0.3; K: 0.5
				A, B, C: D6; D, E, F: 0.8 D6 G, H, I: 0.6 D6 J: 0.5 D6; K: 0.8 D6	A, B, C: 0.9; D, E, F: 0.8 G, H: 0.6 I: 0.3; J: 0.3; K: 0.6

Table III. DESIRED LIGHT INTENSITY CALCULATION FOR POINTS OF INTEREST *P*

[0042] For instance, scenario condition 1 defines that points of interest A, B, and C follow the same reference of D1 (e.g., 0.5@90%, 0.5@40%) while D, E, F follow the reduced value of 0.8·D1. Scenario condition 1 also defines that weighting coefficient for points of interest A, B, C is 0.9 and for D, E, F is 0.7, which means that A, B, C is given a priority of delivering the desired light intensity.

[0043] The general common optimization problem would be defined as an objective function:

$$J_{uk} = J_{en} + J_z + J_{A...K}, \quad (4)$$

with the following components of the objective function:

- J_{en} Light intensity (lamp consumption)
- J_z Light pollution
- $J_{A...K}$ Deviation from the desired lighting at points A-K (with assigned priorities, i.e., weighting coefficients)

and may comprise one or more lamps (individually or comprehensively).

Steady-state illuminance intensity distribution

[0044] A steady-state illuminance intensity distribution (without considering weather and glare effects) at any point p on the street surface as shown in Fig.1. is calculated by:

$$E_i(x, y, z) = \sum_{i=1}^n \frac{I_i(C_i, \gamma_i) \cdot h_i}{\left[(x_i)^2 + (y_i - d_i)^2 + (h_i - z_i)^2 \right]^{\frac{3}{2}}} \quad (5)$$

[0045] Where:

- $I(C_i, \gamma_i)$: the angular luminous flux of each contributing light source (luminaire) i in cd ;
- C_i : the photo-metric azimuth of light path to point p in degree of arc from light source i ;
- γ_i : the vertical photo-metric angle of light path to point p in degree of arc from light source i ;
- h_i : the mounting height of the i^{th} luminaire in m;
- d_i : the boom length of the i^{th} luminaire in m.

[0046] The Photo metric azimuthal angle C can be calculated using:

$$C = 90 + \arcsin \left\{ \frac{x}{\left[\left[(y - d) \cos \sigma - h \sin \sigma \right]^2 + x^2 \right]^{0.5}} \right\} \quad (6)$$

[0047] And the vertical photo metric angle γ_i can be calculated using:

$$\gamma = \arccos \left\{ \frac{h \cos \sigma + (y - d) \sin \sigma}{\left[(y - d)^2 + x^2 + h^2 \right]^{0.5}} \right\} \quad (7)$$

[0048] Where:

- σ : the boom inclination in degree as shown in Fig.4.

[0049] Once obtained, the model from (5) is extended to include weather or glare components from (3).

Dynamic lighting

[0050] A "dynamic lighting" as a term refers to a change in a light intensity over time. This implies a predictive component and adaptation of a lighting to different variables - currently and on the prediction horizon N (e.g., 4h in advance), where

variables indicate road conditions that can be predicted: number (density) of vehicles, cyclists, pedestrians, weather conditions (precipitation, visibility, temperature), etc. The variables are related to a micro location, i.e., a considered lighting segment (in the narrowest sense, this means an individual lamp).

[0051] A sample time, or a time resolution T_s , means a time window in which the lighting control method and system observes the variable or how often it gets a new information. In the below example, the time resolution T_s is 1 minute and for the whole duration of the next minute the system will not get the new information. Hence, the information can be current state of the traffic at the given point and the system would behave as given above (lot of unregistered cars may pass between minutes 3 and 4) or can be summed or averaged for the whole last minute on the number of cars. This time resolution T_s may be chosen on available data and every technical system obtains relevant data in an intelligently chosen way - meaning that if there are lot of unregistered cars between minutes 3 and 4, the sample time may be reduced to e.g., half minute or ten seconds etc. to capture the relevant information.

[0052] The prediction horizon N is a number of future sample times, also called future time steps or time resolutions T_s . For a e.g., 1 minute the time resolution T_s and the prediction horizon N of 120-time steps, that means the lighting control method and system is observing 120 minutes or 2 hours ahead. The prediction of the data can be calculated based on mathematical models and historical data (e.g., number of cars that will pass in next 1 minute, next 2 minutes... next 120 minutes), and obtain an optimal system behaviour with this prediction horizon N . As the observed variables now imply time profile of discrete steps (vectors instead of single values), they are given index k while index $k + 1$ implies next time step of the time resolution T_s in the future. Consistently, variables span until the index $k + N$, which implies N number of the time resolutions T_s in the future.

[0053] In the present control method, both the prediction horizon N and the time resolution T_s are arbitrary parameters and the algorithms will work with any of the chosen.

[0054] The lighting control method and system thereof imposes a continuous, gradual transition between two levels of illumination over two-time intervals. This can be an arbitrary function for intervals of arbitrary duration. In a specific exemplary case, the function is a ramp and a time interval is 1 minute which means that the change in an intensity level from 100% to 85% will change over 15 minutes by 1%. This transition can also be defined by street / city users or persons in charge of managing and maintaining city lighting. In another specific (edge) scenario, the optimization problem can be adapted to the individual lamp and a speed of the pedestrian or vehicle, so as to maintain the same illumination during passage, i.e., reduce when the pedestrian or vehicle is away from the lamp, and amplify when closer. In other words, the lighting system monitors a position and movement of pedestrians or vehicles. These functions can be described as an arbitrary nonlinear law between the states x_k and x_{k+1} :

$$x_{k+1} = f(x_0, u_k) \quad (8)$$

respectively, in a specific linear variant as a common state-space system representation model within the optimization problem and thus model predictive control:

$$x_{k+1} = Ax_k + Bu_k \quad (9)$$

$$y_k = Cx_k + Du_k$$

where y are system outputs related to states y and inputs u with linear dynamics C and D . The criterion function from (4) now takes on a predictive character and is observed on the prediction horizon N with the time resolution of T_s :

$$\sum_k^N Ju_k \quad (10)$$

with an arbitrarily chosen time step between two-time intervals k and $k + 1$ (e.g., 1 minute) on the prediction horizon N (e.g., 1h, which means that k is in the interval $(k = 1, \dots, 60)$).

[0055] A and B are constants for linear systems and in the present invention for a constant weather. If the weather changes from clear to foggy, that means less light gets to the points of interest p from city streetlamps, which results in lower values in B matrix.

$$x_{k+1} = A(V_k)x_k + B(V_k)u_k. \quad (11)$$

[0056] The control method and system thereof additionally comprise dynamically generating prediction data being gradual implementation of weather-changing micro-location data, which can be obtained by a fusion of a publicly available historical data and latest measurements from on-site locations, wherein:

- Weather conditions can include humidity, precipitation, visibility, temperature, and potential additional mathematical variables such as the assessment of precipitation retention on the road, etc., the source of information are meteorological services, and with them the actual on-site measurements and their historical data;
- Road traffic density can include number and type of vehicles, average speed, congestion factor, etc., and potential additional mathematical variables, obtained from navigation services, the nearest traffic counters and actual micro location measurements and their historical data; and
- Pedestrian traffic density can include number of pedestrians and demographic data, and potential additional mathematical variables obtained from city data, public information, and actual micro location measurements and their historical data.

[0057] Dynamically generating prediction data is implemented by one of the groups consisting of physical models, machine learning methods, neural networks, etc., and then finally converted into requirements for the desired lighting at selected points of interest p for a lighting optimization. The term "dynamically" refers to continuously updating prediction data over the prediction horizon N and with the selected time resolution T_s .

[0058] Simultaneous steady-state illuminance intensity distribution and dynamic component is combined into one optimization problem with mutually contradictory components considering the propagation of variables and external conditions on the prediction horizon N and with the selected time resolution T_s of consideration reads:

minimize energy consumption, light pollution, and deviation from the desired lighting at selected points of interest (with priorities) considering: norms for the road category (depending on the time of night), meeting the minimum defined conditions, lighting components at points of interest, the influence of weather conditions at points of interest, lighting transition dynamics, and limitations of light sources (power characteristics, etc.).

[0059] In the selected specific case, the objective function of the above problem is:

$$\min_{u_{i,k}} \sum_{k=1}^N \sum_{j=1}^m \sum_{i=1}^n w_u u_{i,k} + w_r r_{i,j,k} + w_j |x_{j,k} - x_{j,k}^{ref}|, \quad (12a)$$

$$x_{\min} \leq x_{j,k}, \quad j \in S, \quad (12b)$$

$$x_{j,k}^{ref} = f(j, k, V_k), \quad (12c)$$

s.t.

$$x_j = f_{stat}(u_i, l_i, \gamma_j, V_k), \quad (12d)$$

$$x_{j,k+1} = f_{din}(x_{j,k}, u_{i,k}), \quad (12e)$$

$$u_{\min} \leq u_{i,k} \leq u_{\max}, \quad (12f)$$

with notation explained in below table:

Variable	Description
n	Total number of considered individual lamps

(continued)

Variable	Description
i	Index of a single lamp
m	Total number of points of interest p
j	Individual point of interest index
N	Prediction horizon
k	Discrete time step index
u	Control variable - light intensity (0-100%)
x	State variable - the light intensity at the point of interest p
$x_{j,k}^{ref}$	dynamic desired light intensities (dynamic reference values) at points of interest p
r	Light pollution
W	Weighting coefficients (priorities)
S	Set of points of interest to which the quality of lighting (norms) strictly refers
f	Prediction and estimation of the desired lighting level at points of interest
f_{dyn}	Dynamic function of light intensity transition over time Function of illuminance intensity at the point of interest in relation to all considered sources
f_{stat}	considered sources
x_{min}	Minimum allowed lighting intensity stemming from the street lighting norms
u_{min}	Minimum permissible light source intensity
u_{max}	Maximum permissible light source intensity

[0060] Following from (4) and (12), objective function elements are:

$$\begin{aligned}
 J_{en} &= \sum_{k=1}^N \sum_{i=1}^n w_u u_{i,k}, & \text{Light intensity (lamp consumption)} \\
 J_z &= \sum_{k=1}^N \sum_{j=1}^m \sum_{i=1}^n w_r r_{i,j,k}, & \text{Light pollution} \\
 J_{A...K} &= \sum_{k=1}^N \sum_{j=1}^m \sum_{i=1}^n w_f |x_{j,k} - x_{j,k}^{ref}|, & \text{Deviation from the desired lighting at points of interest}
 \end{aligned}$$

[0061] Light pollution is chosen as an additional set $r_{i,j,k}$ of a single or multiple points of interest in the same way as for $x_{j,k}$, with the distinction that desired value to follow is set to zero.

[0062] Constraints from (12) are calculated as:

Constraint:	Obtained from:
(12b)	Street lighting norms requiring the least amount of light on specifically defined point(s) on the road
(12c)	Predetermined streetlight dimming scenarios from tables I and II
(12d)	Spatial coordination-based model of light propagation from (9) and (11)
(12e)	Lighting transition dynamics limitations of the streetlamps, such as (13) or (14)
(12f)	Technical specifications of the luminaire regarding physical limitations, e.g., 0% and 100%

[0063] Some of the exemplary conditions to impose gradual lighting transition dynamics:

$$|x_{k+1} - x_k| \leq \Delta x_{min} \quad (13a)$$

$$|u_{k+1} - u_k| \leq \Delta u_{\min} \quad (13b)$$

where $\Delta x_{\min}$ and $\Delta u_{\min}$ are allowed rate of change, or more elaborate function to ensure smoother transition:

$$x_k \leq \frac{2}{\pi} \text{atan}((k - k_0)T_s) - x_{k_0}, \quad (13c)$$

where k_0 and x_{k_0} are starting time step and value of transient. The gradual lighting transition dynamics can also be imposed by a quadratic formulation of the objective function:

$$\min_{u_{i,k}} \sum_{k=1}^N \sum_{j=1}^m \sum_{i=1}^n u_{i,k}^T W_u u_{i,k} + r_{i,j,k}^T W_r r_{i,j,k} + (x_{j,k} - x_{j,k}^{ref})^T W_j (x_{j,k} - x_{j,k}^{ref}). \quad (14)$$

[0064] In one embodiment, for applying a Model Predictive Control (MPC) algorithm, the proposed objective function is given in (12). Figure 2 shows the proposed points of interest for illuminance intensity calculation. The main objective of the algorithm is to control the illuminance intensity at the selected points of interest i.e., to control streetlamps illuminating these points.

[0065] Table IV. shows x, y and z coordinates of the points of interest A, B, C, D, E, and G that have been chosen in this illustrative case study of a street segment with respect to four contributing lamps.

Table IV - COORDINATES OF THE INTERESTING POINTS FOR THE THREE SELECTED CONTRIBUTING LUMINAIRES

(x,y)	A	B	C	D	E	G
l_1	(0, 3.5)	(0, 0.583)	(0, 6.417)	(4.5.5, 1.75)	(4.5, 6.417)	(0, 9)
l_2	(-30, 3.5)	(-30, 0.583)	(-30, 6.417)	(-25.5, 1.75)	(-25.5, 6.417)	(-30, 9)
l_3	(30, 3.5)	(30, 0.583)	(30, 6.417)	(34.5, 1.75)	(34.5, 6.417)	(30, 9)
l_4	(-60, 3.5)	(-60, 0.583)	(-60, 6.417)	(-55.5, 1.75)	(-55.5, 6.417)	(-60, 9)

[0066] Table V. shows the illuminance intensities of the chosen points of interest in this case study.

Table V - ILLUMINANCE INTENSITIES OF INTERESTING POINTS (A, B, C, D, E, AND G)

Points of interests	A	B	C	D	E	G
Illuminance intensities E_x	32	36	26	33	25	20

[0067] After determining the points of interest p according to the available illuminance intensity measurements, the illuminance intensities are calculated at these points in terms of the lamp luminous flux $I(C, \gamma)$.

[0068] The illuminance intensity at e.g., point A can be calculated from (5):

$$E_A(x_A, y_A, z_A) = \frac{I_1(C_1, \gamma_1) \times 11}{\left[(0)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} + \frac{I_2(C_2, \gamma_2) \times 11}{\left[(-30)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} + \frac{I_3(C_3, \gamma_3) \times 11}{\left[(30)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} + \frac{I_4(C_4, \gamma_4) \times 11}{\left[(-60)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} \quad (15)$$

where the point A is affected by four lamps. Substituting with the available values of the variables in the above equations gives:

$$E_A(x_A, y_A, z_A) = 0.0072I_1 + 0.0003I_2 + 0.0003I_3 + 0.0000I_4$$

[0069] And for the other remaining points:

$$E_A(x_A, y_A, z_A) = 0.0072I_1 + 0.0003I_2 + 0.0003I_3 + 0.0000I_4 \quad (16)$$

$$E_B(x_B, y_B, z_B) = 0.0082I_1 + 0.0003I_2 + 0.0003I_3 + 0.0000I_4$$

$$E_C(x_C, y_C, z_C) = 0.0054I_1 + 0.0003I_2 + 0.0003I_3 + 0.0000I_4$$

$$E_D(x_D, y_D, z_D) = 0.0085I_1 + 0.0005I_2 + 0.0002I_3 + 0.0001I_4$$

$$E_E(x_E, y_E, z_E) = 0.0060I_1 + 0.0005I_2 + 0.0002I_3 + 0.0001I_4$$

$$E_G(x_G, y_G, z_G) = 0.0039I_1 + 0.0003I_2 + 0.0003I_3 + 0.0000I_4$$

[0070] In a matrix form:

$$\begin{bmatrix} E_1(k+1) \\ E_2(k+1) \\ E_3(k+1) \\ E_4(k+1) \\ E_5(k+1) \\ E_6(k+1) \end{bmatrix} = \begin{bmatrix} E_1(k) \\ E_2(k) \\ E_3(k) \\ E_4(k) \\ E_5(k) \\ E_6(k) \end{bmatrix} + \begin{bmatrix} 0.0072 & 0.0003 & 0.0003 & 0.0000 \\ 0.0082 & 0.0003 & 0.0003 & 0.0000 \\ 0.0054 & 0.0003 & 0.0003 & 0.0000 \\ 0.0085 & 0.0005 & 0.0002 & 0.0001 \\ 0.0060 & 0.0005 & 0.0002 & 0.0001 \\ 0.0039 & 0.0003 & 0.0003 & 0.0000 \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (17)$$

[0071] Using state-space system notation from (9), then:

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ x_3(k+1) \\ x_4(k+1) \\ x_5(k+1) \\ x_6(k+1) \end{bmatrix} = \begin{bmatrix} 0.0072 & 0.0003 & 0.0003 & 0.0000 \\ 0.0082 & 0.0003 & 0.0003 & 0.0000 \\ 0.0054 & 0.0003 & 0.0003 & 0.0000 \\ 0.0085 & 0.0005 & 0.0002 & 0.0001 \\ 0.0060 & 0.0005 & 0.0002 & 0.0001 \\ 0.0039 & 0.0003 & 0.0003 & 0.0000 \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} y_1(k+) \\ y_2(k+) \\ y_3(k+) \\ y_4(k+) \\ y_5(k+) \\ y_6(k+) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_1(k+) \\ x_2(k+) \\ x_3(k+) \\ x_4(k+) \\ x_5(k+) \\ x_6(k+) \end{bmatrix} \quad (19)$$

[0072] Sampling time is chosen as 5 minutes and six main points of interest (A, B, C, D, E, G) are observed, corresponding to critical points (with priority) A and B and less critical points C, D, E, and G, and the weights are selected correspondingly as $w = [2.5, 2.3, 0.8, 1.2, 1, 0.7]$

[0073] Table VI shows luminaire characteristics and Table VII technical specifications of a considered industrial lamp.

Table VI LUMINAIRE CHARACTERISTICS

Characteristics	Luminaire values
Pole distance	30.000 m
h -Light spot height	11.000 m
s -Light spot overhang	0.100 m
σ -Boom inclination	0.0
d -Boom length	0.000 m
Annual operating hours	4000 h: 100%, 120W
Consumption	3960.0 W/km
ULR/ULOR	0.00/0.00
Max. luminous intensities Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.	$\geq 70 : 528 \text{ cd/klm}$ $\geq 80 : 49.4 \text{ cd/klm}$ $\geq 90 : 0.00 \text{ cd/klm}$
Luminous intensities The luminous intensity values in [cd/klm] for calculations of the luminous intensity class refer to the luminaire luminous flux according to EN 13201:2015	$G * 3$
Glare index class	D.6

Table VII TECHNICAL SPECIFICATIONS OF A LUMINAIRE

Technical Specifications	luminaire values
P	120 W
ϕ_{Lamp}	15600 lm
$\phi_{Luminaire}$	14337 lm
μ	92%
Luminous efficacy	119.5 lm/W
CCT	3000 K
CRI	81 W

[0074] Fig. 5. presents the MPC-based optimization results. From this figure, it can be observed that reference tracking goal at the critical points A and B is satisfied as an optimization priority. Other points C, D, E, and G are left with the criterion of trade-off between illumination and energy savings. It is important to emphasize that all four lamps contribute to light up those points such that the intensity of the fourth lamp can be further increased to illuminate points D and E but due to points A and B priority this is not the case.

[0075] In case of a more continuous transitions between setpoint values of a lighting profile, a constraint:

$$\Delta u_{min} \leq u(k+1) - u(k) \leq \Delta u_{max} \quad (20)$$

is now chosen with $\Delta u_{min} = -250 \text{ W}$ and $\Delta u_{max} = 250 \text{ W}$, which in this particular case means that a luminaire is allowed to change its power by 250 W during the sample time period T_s , set as 5 min in this case.

[0076] Adjusting the light intensity of the streetlight luminaires with respect to the surrounding conditions not only can save energy, but also can increase the utilization efficiency of the system (increase luminaire's lifespan, improve lumi-

naire's maintenance, etc.). Developing an appropriate control system is essential to achieve such optimal utilization. The results obtained showed that the illuminance intensities at the surface of the street can be predicted over a prediction horizon N and the luminous intensity of the street luminaires can be adjusted accordingly.

[0077] In the following, an embodiment of a centralized prediction-based controllable lighting system is described. Fig. 7 shows the centralized prediction-based controllable lighting system comprising software systems and connectivity and telemetry exchange modules to and between a control device of each streetlamp and a central computer or computer cloud, the system further comprising:

- one or more streetlamps which are controllable to deliver a desired amount of light intensity at a predetermined set of points of interest p over a prediction horizon N with a time resolution of T_s ;
- a one or more first databases configured to store, update and output a historical and latest weather, traffic, pedestrian and road condition data;
- a plurality of AI sub-modules configured for implementing a modelling method and generating prediction data over the prediction horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions at the predetermined set of points of interest p , the prediction data are generated comparing a respective historical weather, traffic, pedestrian and road data and the latest weather, pedestrian, traffic, and road condition data, wherein the plurality of AI sub-modules is selected from one of the groups consisting of physical models, machine learning methods, or neural networks;
- a second database configured to store and update predetermined streetlight dimming scenarios at the predetermined set of points of interest p for one or more streetlamps for delivering the desired amount of light intensity, each predetermined streetlight dimming scenario is based on the generated prediction data and wherein each predetermined streetlight dimming scenario has assigned dynamic reference values for the predetermined set of points of interest p over the prediction horizon N with the time resolution of T_s ;
- a central computer or a computer cloud with executable Model Predictive Control (MPC) algorithm configured to perform: selecting dynamic reference values and calculating a spatial coordination-based model of light propagation at the predetermined set of points of interest p over the prediction horizon N with the time resolution of T_s , and calculating a sequence of the control actions over the prediction horizon N with the time resolution of T_s for the one or more street lamps and provides control actions to control devices of the one or more street lamps to change an applied voltage, power or current; and one or more interfaces configured for processing and formatting the control actions of the Model Predictive Control (MPC) algorithm to a third database, the third database is connected to processors configured for outputting the control actions to the control devices of the one or more street lamps.

[0078] The software systems may be aided by suitable protocols which act as distributed control means, standards, frameworks, and mechanisms for self-regulating large volumes of distributed entities to achieve a collective objective or benefit. Said connectivity means typically include standard communication technologies such as fixed and wireless telephony and mobile networks (GPRS, 1-5G, LTE), local communication technologies such as WiFi, Z-Wave, Zigbee, mesh networks, Powerline or signals carried over an electrical circuit, together with leverage of the Internet and remote computers and/or cloud hosted components and technologies, and on end customer devices.

[0079] The plurality of AI sub-modules, one or more first databases, second database, Model Predictive Control (MPC) algorithm and one or more interfaces are arranged on a central computer server or remotely in a computer cloud. The first, second and third database can be configured as a one database.

[0080] Historical weather, traffic, pedestrian and road condition data and latest (real-time most recent on-site) data is stored in one or more first databases, whether independent or part of a larger supervisory system, such as SCADA (supervisory control and data acquisition) or ERP (enterprise resource planning). The latest weather and road condition data are obtained from on-site meteorological sensors or remote sources on meteorological information and combinations thereof; pedestrian data are obtained from pedestrian mobile phones, wearable devices, traffic counters, video and acoustic sensors, or from remote sources on traffic information and combinations thereof; and the latest traffic data are obtained from on-site traffic counters, video and acoustic sensors, and from remote sources on traffic information, and combinations thereof. The collected data is further processed on a central computer or remotely in a computer cloud. Machine learning algorithms and/or neural networks algorithms, depicted as AI sub-modules in Fig. 7, are executed to obtain estimated future values of variables on prediction horizon of N with a sample time/time resolution of T_s , which are further used in the MPC algorithm. The outputs of the MPC algorithm are post-processed in interfaces to put in appropriate format and ready to be accepted again by the corresponding one or more databases.

[0081] Yet further provided is a computer being configured to perform a method according to the invention such as a central computer or remotely in a computer cloud and comprising an interface to a network of lamps. The computer may execute a program with a graphical user interface, allowing a user to comfortably adjust of input data to changes in the system.

[0082] Also provided is a computer program enabling a processor to carry out the method according to the invention and as specified above.

[0083] Further provided is a record carrier storing a computer program according to the invention may be provided, for example a CD-ROM, a DVD, a memory card, a diskette, internet memory device, a central computer or remotely in a computer cloud, or a similar data carrier suitable to store the computer program for optical or electronic access.

Claims

1. A centralized model predictive lighting control method for one or more streetlamps, the method is **characterized** by the following steps:

- providing a centralized prediction-based controllable lighting system for one or more street lamps, the system comprising software systems and protocols, connectivity and telemetry exchange modules to and between a control device of each streetlamp and a central computer or computer cloud, wherein each streetlamp light intensity is activated by a control action;
- obtaining of historical weather, traffic, pedestrian and road condition data;
- obtaining a latest weather, pedestrian, traffic, and road condition data;
- implementing a modelling method and generating prediction data for a prediction horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions at a predetermined set of points of interest p , the prediction data are generated comparing a respective historical weather, traffic, pedestrian and road data and the latest weather, pedestrian, traffic, and road condition data, each generated prediction data is implemented by the modelling method by one of the group consisting of physical models, machine learning methods, or neural networks;
- calculating a spatial coordination-based model of light propagation at the predetermined set of points of interest p ; and
- generating a predetermined streetlight dimming scenario at the predetermined set of points of interest p for one or more streetlamps for delivering a desired amount of light intensity over the prediction horizon N with the time resolution of T_s , the predetermined streetlight dimming scenario is based on the generated prediction data;
- selecting dynamic reference values for the predetermined set of points of interest p , the dynamic reference values are selected according to the generated predetermined streetlight dimming scenario;
- implementing a Model Predictive Control (MPC) algorithm configured to calculate light intensities of one or more streetlamps considering the dynamic reference values, assigned weighting coefficients and calculated spatial coordination-based model at the predetermined set of points of interest p , the Model Predictive Control (MPC) algorithm performs calculating a sequence of the control actions over the prediction horizon N with the time resolution of T_s for the one or more street lamps and communicates control actions to the control devices of the one or more street lamps to change an applied voltage, power or current.

2. The method according to claim 1, wherein the method further comprising setting of the prediction horizon N , time resolution T_s , number of lamps, number of the predetermined set points of interest p for one or more street lamps and weighting coefficients determining a significance of each point of interest p .

3. The method according to claim 1, wherein the step of generating the predetermined streetlight dimming scenario is based on scenario conditions, the scenario conditions are depending on a day light duration, weather, traffic and pedestrian conditions, wherein the each of said conditions has an assigned variable and threshold used for selecting the dynamic reference values.

4. The method according to claim 3, wherein the assigned variables and thresholds include precipitation level, visibility data, traffic density, diversity and density of pedestrians.

5. The method according to claim 3, wherein the predetermined streetlight dimming scenario is continuously and real-time updated over the prediction horizon N with the time resolution of T_s .

6. The method according to claim 1, wherein performing a prediction of the light intensities at each of the predetermined set of points of interest p is based on the dynamic reference values, weighting coefficients and the spatial coordination-based model, the spatial coordination-based model is a function of light intensities reaching the predetermined set of points of interest p from one or more streetlamps considering a distribution of the light intensities in a space in different weather conditions and taking into account reflections from all light sources.

7. The method according to claim 6, wherein the spatial coordination-based model includes calculated light intensities in the predetermined set of points of interest p based on a steady-state light intensity distribution and a continuous, gradual transition between two levels of light intensities over two-time intervals with an arbitrary rate of change.

8. The method according to any one of the preceding claims, wherein the Model Predictive Control (MPC) algorithm performs minimizing an objective function over the prediction horizon N with the time resolution of T_s , the objective function comprising calculating a light intensity J_{en} , light pollution J_z , and deviation $J_{A...K}$ from the desired lighting at the predetermined set of points of interest p considering:

- a- calculated constraints for street lighting norms requiring the least amount of light at the predetermined set of points of interest p at a street surface;
- b- generated predetermined streetlight dimming scenario at the predetermined set of points of interest p ;
- c- calculated spatial coordination-based model of light propagation at the predetermined set of points of interest p ;
- d- calculated constraint for lighting transition dynamics limitations of the streetlamps; and
- e- technical specifications of each streetlamp.

9. The method according to claim 1, wherein further comprising saving the latest weather, pedestrian, traffic, and road condition data and updating the historical weather, traffic, pedestrian and road data.

10. The method according to claim 1, wherein the latest weather and road condition data are obtained from onsite measurements of meteorological sensors or remote sources on meteorological information and combinations thereof; pedestrian data are obtained from pedestrian mobile phones, wearable devices, traffic counters, video and acoustic sensors, or from remote sources on traffic information and combinations thereof; and the latest traffic data are obtained from onsite measurements of traffic counters, video and acoustic sensors, and from remote sources on traffic information, and combinations thereof.

11. A centralized prediction-based controllable lighting system comprising software systems and connectivity and telemetry exchange modules to and between a control device of each streetlamp and a central computer or computer cloud, the system further comprising:

- one or more streetlamps which are controllable to deliver a desired amount of light intensity at a predetermined set of points of interest p over a prediction horizon N with a time resolution of T_s ;
- a one or more first databases configured to store, update and output a historical and latest weather, traffic, pedestrian and road condition data;
- a plurality of AI sub-modules configured for implementing a modelling method and generating prediction data over the prediction horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions at the predetermined set of points of interest p , the prediction data are generated comparing a respective historical weather, traffic, pedestrian and road data and the latest weather, pedestrian, traffic, and road condition data, wherein the plurality of AI sub-modules is selected from one of the groups consisting of physical models, machine learning methods, or neural networks;
- a second database configured to store and update predetermined streetlight dimming scenarios over the prediction horizon N with the time resolution of T_s at the predetermined set of points of interest p for one or more streetlamps for delivering the desired amount of light intensity, each predetermined streetlight dimming scenario is based on the generated prediction data and wherein each predetermined streetlight dimming scenario includes assigned dynamic reference values for said predetermined set of points of interest p ;
- a central computer or a computer cloud comprising executable Model Predictive Control (MPC) algorithm configured to perform:

- a) selecting dynamic reference values and calculating a spatial coordination-based model of light propagation at the predetermined set of points of interest p over the prediction horizon N with the time resolution of T_s , and
- b) calculating a sequence of the control actions over the prediction horizon N with the time resolution of T_s for the one or more streetlamps and providing control actions to control devices of the one or more streetlamps to change an applied voltage, power or current; and

- one or more interfaces configured for processing and formatting the control actions of the Model Predictive Control (MPC) algorithm to a third database, the third database is connected to processors configured for outputting the control actions over the prediction horizon N with the time resolution of T_s to the control devices

of the one or more streetlamps.

5 12. The lighting system according to claim 11, wherein the latest weather and road condition data are obtained from on-site meteorological sensors or remote sources on meteorological information and combinations thereof; pedestrian data are obtained from pedestrian mobile phones, wearable devices, traffic counters, video and acoustic sensors, or from remote sources on traffic information and combinations thereof; and the latest traffic data are obtained from onsite traffic counters, video and acoustic sensors, and from remote sources on traffic information, and combinations thereof.

10 13. The lighting system according to claim 11, wherein the plurality of AI sub-modules, one or more first databases, second database, third database, Model Predictive Control (MPC) algorithm and one or more interfaces are arranged on the central computer or remotely in the computer cloud, said databases are configured as a one database.

15 14. A computer program comprising program code that, when executed by a processor, enables the processor to carry out a method according to any of the claims 1 to 10.

15 15. A record carrier storing a computer program according to claim 14.

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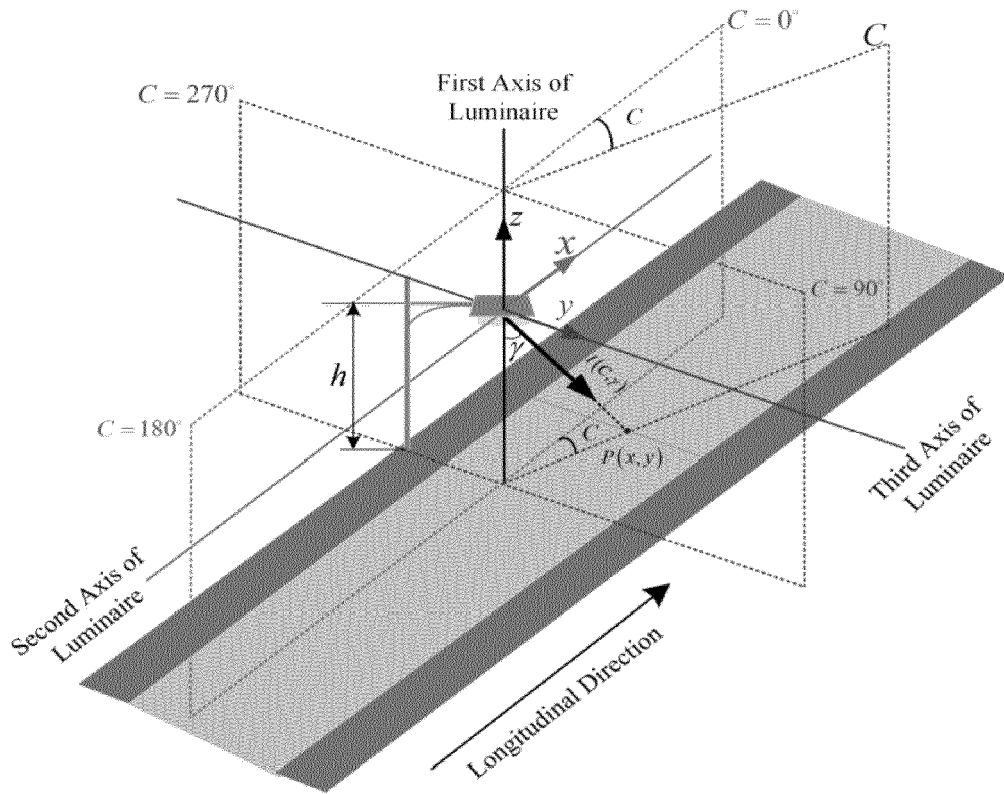


Fig. 1

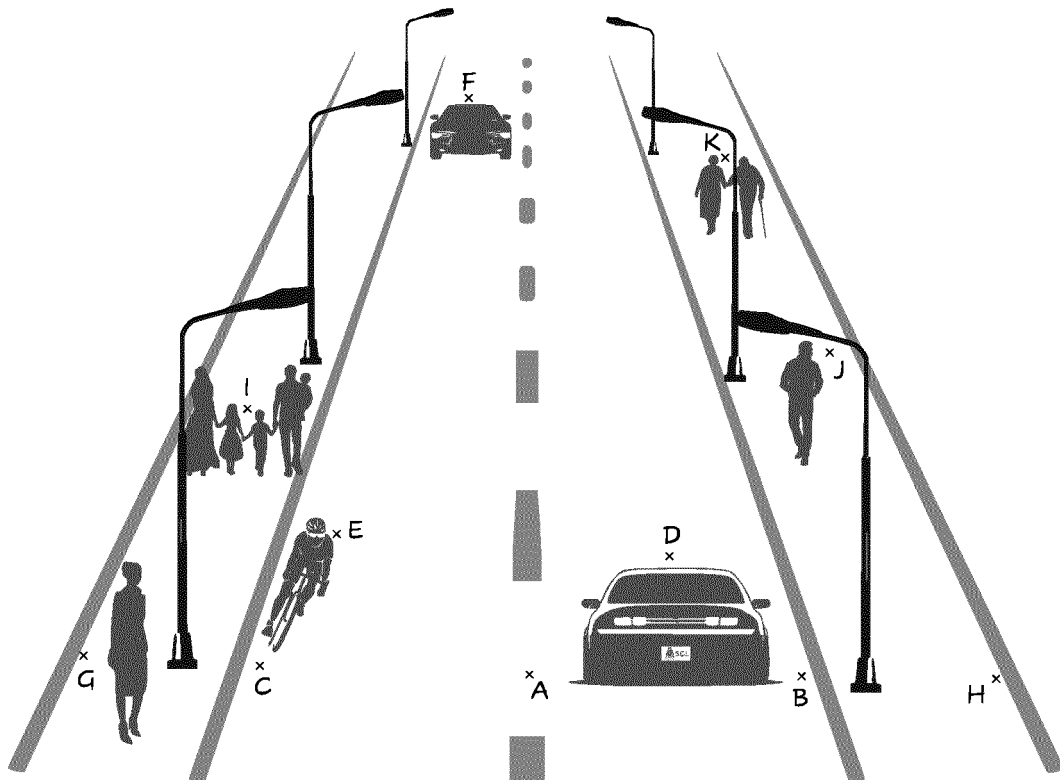


Fig. 2

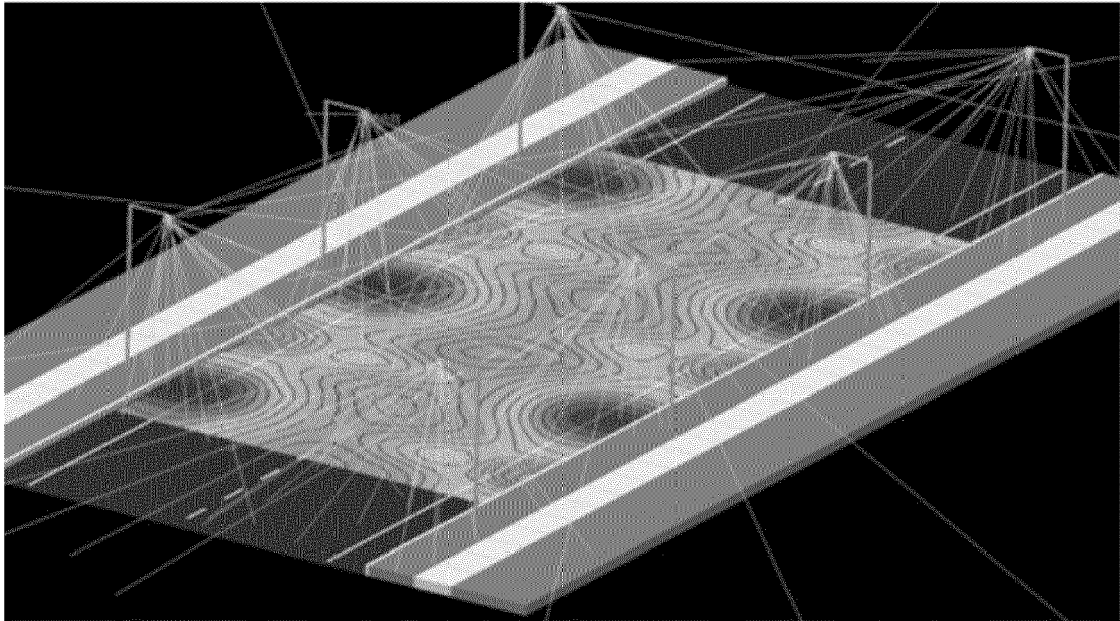


Fig. 3

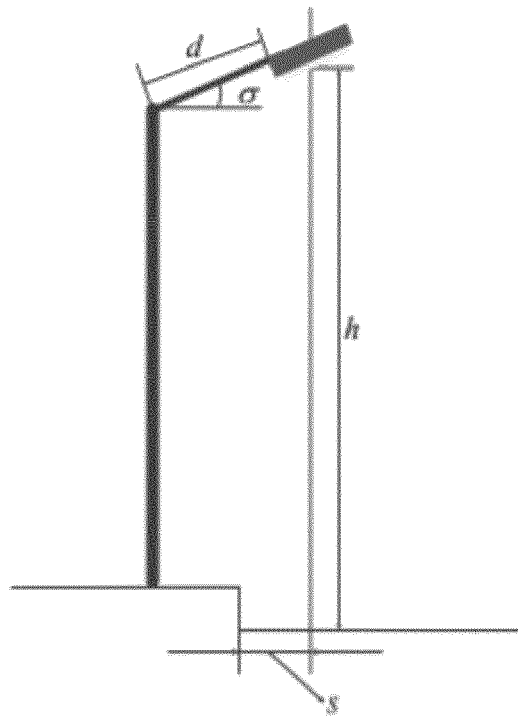


Fig. 4

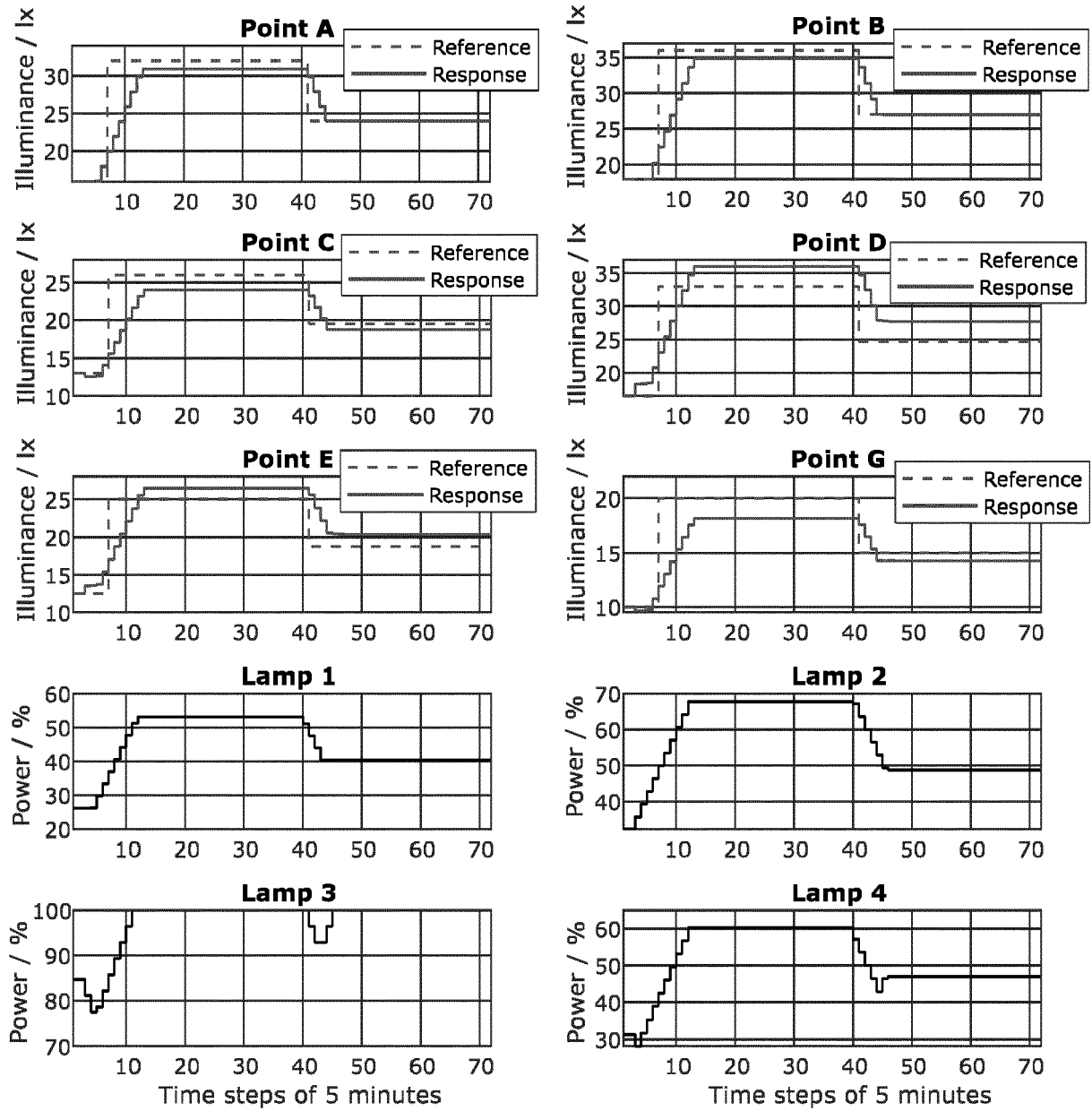


Fig. 5

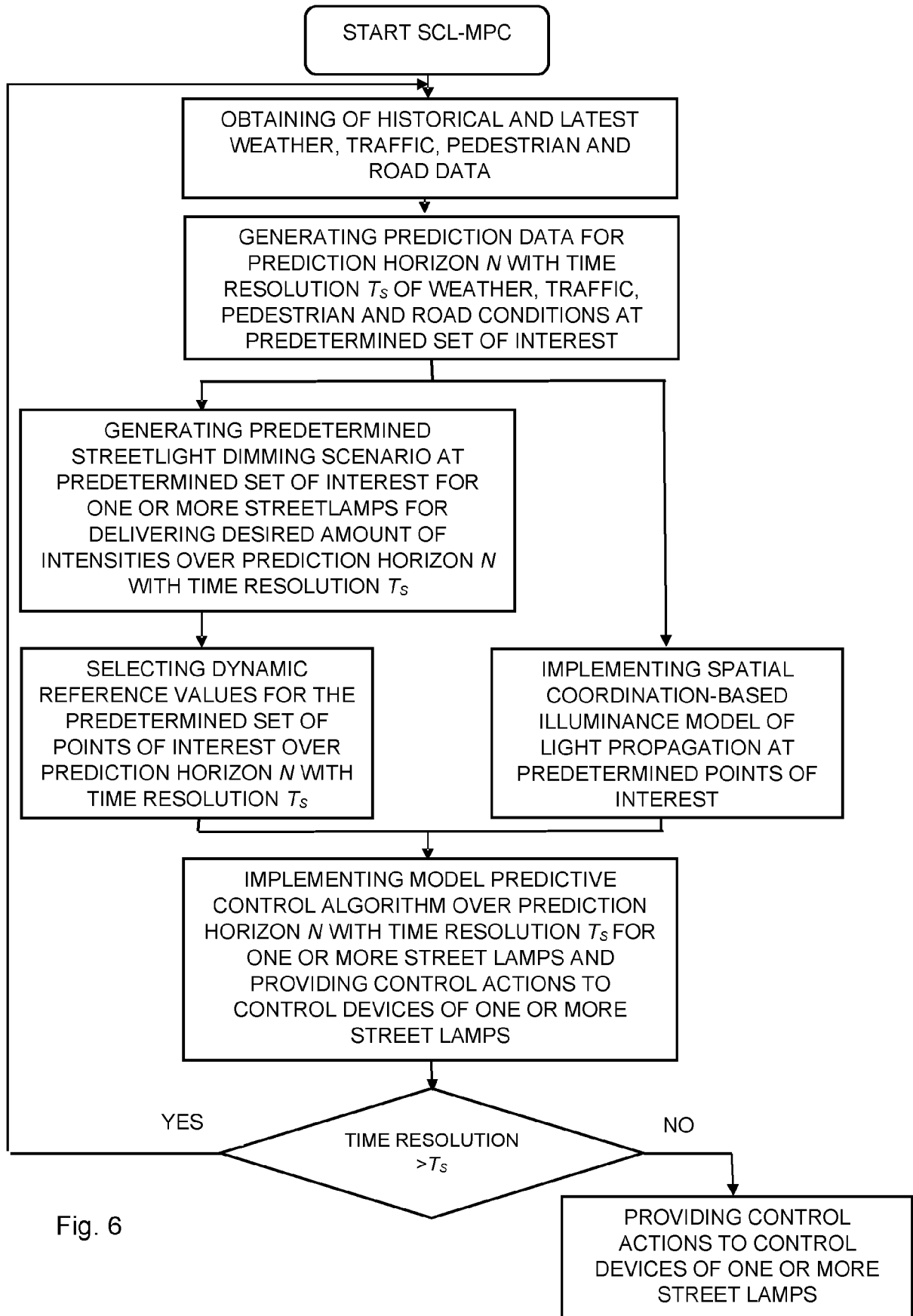


Fig. 6

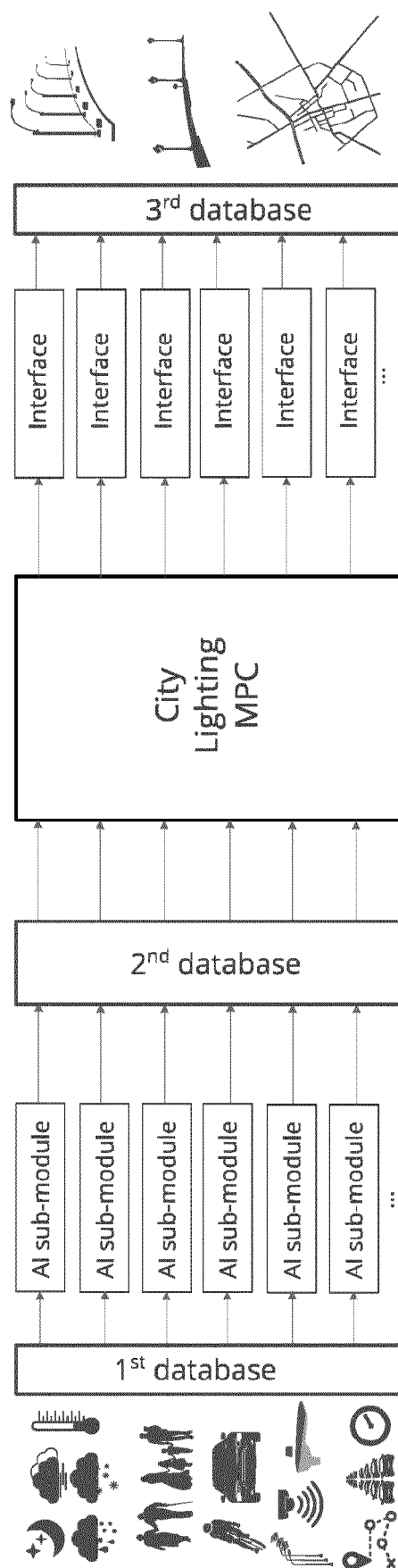


Fig. 7



EUROPEAN SEARCH REPORT

Application Number

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EPO FORM 1503 03.82 (P04C01)

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A	* paragraphs [0022]-[0024], [0035], [0037] and [0039]; figures 1 and 2 *	8	H05B47/19 G05B17/02
Y	US 2022/128206 A1 (WEITLANER ROBERT [AT]) 28 April 2022 (2022-04-28)	1-7, 9-15	
A	* paragraphs [0062], [0131]-[0139]; figures 1-3 and 6-8 *	8	
T	Anonymous: "Model predictive control - Wikipedia", / 21 March 2017 (2017-03-21), XP055357288, Retrieved from the Internet: URL:https://en.wikipedia.org/wiki/Model_predictive_control [retrieved on 2017-03-21] * the whole document *		
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			H05B G05B
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 2 May 2023	Examiner Erskine, Andrew
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