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Daylight Harvesting to Reduce Energy Consumption in Lighting

Evaluating different control methods to maintain a constant illuminance

Master's thesis in Systems, Control and Mechatronics

Max Reidal and Elmer Nordqvist

Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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Cover: Picture of the MIMO lighting system used in the thesis

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Abstract

In this thesis different methods for daylight harvesting are investigated and evaluated with the goals of determining the feasibility of different methods both in SISO and MIMO controlled indoor light systems. The main points of the evaluation are energy savings and occupants detectability of the control. Two state space models are considered for creating controllers, one where rate of change is controlled, and one where total light output of the light sources is controlled. Several different methods are evaluated, like simple PID-controllers, Linear programming, MPC and LQR. Focus has been on evaluating the controllers on physical light systems with the goal of running the implementations on micro-controllers. In the SISO case it is found that a simple I-controller performs best, while for the MIMO case LQR and Linear programming was found to have the best performance. Tests performed on a daylight profile of a sunny day in early May found that under those specific circumstances both the SISO and MIMO controllers were able to save about 50% energy in comparison to an uncontrolled system. The SISO system was also tested on a partly cloudy day in late April, on that day it was found to save about 20% energy as compared to an uncontrolled system. However, the long term energy savings depend largely on the local climate, and the size and facing of windows in the room where the system is implemented.

Keywords: Daylight harvesting, Daylight compensation, Illuminance control, light control, Energy savings in lighting

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Max Reidal and Elmer Nordqvist, Gothenburg, June 2020

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1 Introduction

1.1 Background

Interior lighting is responsible for 15-30% of total energy consumption in Scandinavia [1]. One way to reduce this figure that has been implemented over the last years is the changing from regular light bulbs to more energy efficient forms, for example LEDs. LEDs consume less energy while emitting the same amount of light. While this is an improvement there exists ways to further decrease the energy consumption and lifespan of the light armatures. One way to do this is by implementing automatic control of light armatures, so that they decrease their output when there is a large amount of daylight present. Such a strategy is called daylight harvesting. This saves energy as the light armatures use less energy during bright light conditions. For LED lights it also increases the lifespan of the armatures, as the lifespan of LED lighting is largely determined by the internal heat, which is reduced at lower light output.

1.2 Previous work

The control of illuminance has previously been studied in many areas for several purposes. One such area is controlling the complete spectrum of visible light [2]. Such control can be made to either maintain a constant daylight spectrum or follow the dynamically changing daylight spectrum by measuring and mimicking the spectrum of the outside lighting. Most works, however, focus on controlling the luminous flux of the lights in order to achieve a desired level of illuminance, see e.g. [3]–[10].

It has been shown in [2] that it is possible to control the light spectrum in a small room using spectrally tunable lighting systems. The results showed that using the spectrally tunable lighting system to compensate the light spectrum entering the room externally can save 25% energy for lighting as opposed to having the lighting system constantly outputting a full daylight spectrum in a small room of 15 m^2. [3] analysed potential energy savings of three different control systems in an educational building. The three systems consisted of two closed loop systems and an open loop system. The difference between the closed loop systems was that one had light sensors positioned at each luminarie, allowing each luminarie to be dimmed individually, while the other system had a centrally positioned light sensor. The open loop system had a sensor placed outside the building, which therefore only measures the daylight and not the artificial light. The results showed that the open loop system yielded the most energy savings, 46% as compared to having the lights fully on at all times. However, this system consistently performed far below the desired illuminance level. The closed loop system with a sensor at each luminarie came closest to the desired illuminance level and yielded energy savings of 34%.

[4] implemented a daylight compensation lighting control system in one floor of a university building consisting of two laboratories, a corridor and two offices. It was found that energy savings relied heavily on the cardinal orientation of the rooms. The greatest energy savings were achieved in a corner office which had windows towards the south-west and south-east, providing a large amount of daylight on sunny days, 27% energy savings were achieved there. The other office yielded energy savings of 16%, while the laboratories yielded 6% and 3% energy savings. [5] constructed a lighting system which could achieve a user specified illuminance and colour on a desk. This system used a colour sensor placed on the desk in order to directly measure the illuminance and colour temperature. The control system optimised the lighting in order to reduce current while following the user input.

A case study of a factory in China found that large energy savings were possible, by implementing daylight control [6]. The results showed that implementing a simple on/off control, where the lights turned off when enough daylight entered the factory space, could save 36.1% energy, as opposed to always having the lights on. It was also found that implementing dimming control could save up to 41.5% energy. However, it was also found that these two control systems increased the energy cost for heating in the factory by 7.1% and 8.7% respectively. The net energy consumption decreased for both control systems, as the energy savings in lighting outweighed the increased energy cost in heating.

In [7] a novel way of measuring the daylight component of illuminance in a work area was introduced. This was done by dimming the light used using pulse width modulation (PWM), and measuring the daylight component during the short time period when the light was turned off. This measurement could then be used to decide what dimming level the light should be on for the next time step in order to maintain a desired illuminance in the work area. In [8] a lighting control system with occupancy sensors and light sensors located at each luminaire was considered. Two control methods are compared, one using PI-control rule and one using an optimisation approach. The optimisation approach consisted of a linear optimisation problem, with the objective of minimising the power consumption of the luminaries, while also achieving a desired illuminance in each area. The optimisation approach came closest to the desired illuminance levels, while the PI-control had higher energy savings, at the cost of consistently being below desired illuminance levels.

A method for approximating illuminance at a workspace plane by illuminance measurements from sensors located at the ceiling is proposed in [9]. The illuminance levels at the workspace plane is approximated trough a calibration step where the room is dark, and all lights are set to a reference dim level. The illuminance at each workspace, and at each sensor in the ceiling is then measured. Using this a simplified linear model can be constructed between the illuminance at the sensors and the illuminance at the workspace. Simulation results showed that when combining this model with a light control system the actual illuminance levels at the workspace were much closer to the reference value than if the control was made on the sensor illuminance directly. The control system used in this case was solving a linear optimisation problem at each time step, which calculated the worst case model parameters and from this minimised the dim level of all lamps while maintaining required illuminance levels according to the worst case model. When using the model the minimum achieved illuminance at the workspaces over the simulation varied at most 20 lx from the reference value, while when directly controlling the illuminance at the sensor locations the minimum achieved illuminance at the workspace was between 60 and 120 lx below the reference value.

In [10] two different PI-controllers for daylight control was implemented and tested. One classical PI-controller and one PI-controller with offset. This was done as it had been noted that the classical PI-controller tended to under-illuminate surfaces, which the PI-controller with offset fixed. This daylight control system was simulated in an office, split into zones with a luminaire and sensor each. The first implementation had a separate PI-controller for each luminaire. This uncovered some problems, as it lead to some zones being under-illuminated in certain conditions, where one luminaire was at max power and its zone was still under-illuminated, while neighbouring luminaries were at lower than max power. The proposed solution was to implement networking in the daylight control, so that if a luminaire reached its maximum power and its zone was still under-illuminated, the setpoints of neighbouring luminaries were increased.

From the literature it can be concluded that controlling light with traditional control systems is possible and it is a good way to implement daylight harvesting, using control theory to keep illuminance at a fairly constant level by using lighting systems to compensate daylight. Both in Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) systems. Furthermore it appears to be possible to control lighting systems by describing it as a linear optimisation problem and solving it to find an ideal solution.

The potential for energy savings seems largely dependent on the cardinal facing of the windows, as well as the climate of the region. Regions with less daylight will have less potential for energy savings by daylight compensation than regions with more daylight.

The literature proves that it is possible to implement daylight harvesting strategies, and that it is possible to save energy with it. For SISO systems, PI-control seems to be the most common way of control, while for MIMO systems, either decoupled PI-control or solving linear optimisation problems by linear programming seems to be common ways of control.

1.2.1 Energy savings by daylight harvesting

According to the literature it seems possible to save between $10-40\%$ energy during use by implementing daylight harvesting in office environments. These numbers depend on a lot of factors such as size and shape of windows, the facing of the windows in relation to the cardinal directions and weather. A way to further increase the savings appear to be implementation of occupancy sensors to detect if a user is in the area of interest and only activate the lighting if that is the case, or using a lower setpoint when the area is unoccupied.

When it comes to the potential energy saved there is one potential problem in the estimations. Most of the articles approximations of energy savings are based upon studies done before 2011. Since then a change from light bulbs to more energy efficient alternatives has been done in the European union. This has driven down the total energy consumption of lighting, meaning that the percentage of energy consumed by lighting compared to total energy consumption is most likely lower at the time of this thesis. The relative potential energy savings of implementing daylight control systems should however still be accurate, as that is usually compared to the energy consumption of the lighting system without control.

1.3 Objective

The objective of this thesis is to evaluate the feasibility and performance of different methods of implementing daylight harvesting. This will be done by testing on a physical system to evaluate different control methods. Desirable properties of the control system is that it can save energy as compared to an uncontrolled lighting system while maintaining a desired illuminance level. From these points the following research questions are formulated:

1.3.1 Research questions

- Is it possible to control illuminance with a lighting system such that it stays close enough to constant to be undetectable by occupants by regulating the output from light armatures as compensation for changes in ambient lighting?
  - Which kind of controller is most suitable for controlling small systems with one sensor and few light sources?
  - Which kind of controller is most suitable for controlling large systems with many sensors and light sources?
- How will the energy cost of a light armature during its entire lifespan change, both in energy upkeep and increase of lifespan, when using a control method where a lighting system is only used to maintain a desired illuminance level as opposed to always being static?

These questions will be answered in this Thesis.

1.3.2 Limitations

The controllers will be evaluated on physical systems, limited simulations will be performed but the interest is in the performance of the controllers on an actual physical system. The performance will also be evaluated in a southern Swedish coastal climate, which might limit the amount of sunny days in which the system can be tested. Another constraint is the goal of implementing the systems on micro-controllers. This limits the possibility of using processes that require large online computational power such as neural networks. The synthesises of controllers and similar steps that are usually done offline will be allowed to be done offline. New methods of dimming will not be created and already commercially available systems will be used to simplify the interface with the lamps whenever possible. Illuminance is the only aspect of light that will be controlled.

1.4 Structure of the thesis

In chapter 2 the background knowledge needed for the thesis is given. In section 2.1 the basic physical properties of light needed for control is explained, the regulations on illuminance levels is also explained, as well as the detectability of changes in illuminance. Lastly, the existing methods for how to control light output of luminaries is explained. In section 2.2 the basic knowledge of the different controllers used in this thesis is given, the state space model needed for control of illuminance is also constructed.

Chapter 3 explain all the steps that has been taken over the duration of the thesis work to produce the results, which are presented in chapter 4.

Chapter 5 discuss the results and methods used in the thesis.

Finally, the conclusions, answers to the research questions of the thesis as well as potential future works are presented in chapter 6.

2

Theory

2.1 Light

In this thesis light is viewed in photometric terms, that is the human perception of light. The human eye can see light in the wavelengths between 370 to 730 nm of the electromagnetic spectrum, the sensitivity of the eye to this light is lower at the edges, with a peak at 555 nm which is perceived as green light. The eye is less sensitive to red and blue light, as these are closer to the wavelengths the human eye cannot perceive. As such there are photometric units for measuring human eye perception of light. The most basic metric is luminous flux, with the SI unit lumen (lm), which can simply be described as "amount of light". It is related to the radiometric unit Watt (W) trough the CIE 1924 luminous efficiency function which for each wavelength of electromagnetic radiation gives the human eye responsiveness to that wavelength. The metric mostly used in this thesis is illuminance, with the SI unit lux ($lx = lm/m^2$), which is luminous flux per area and therefore describes how illuminated an area is [11].

Light is additive, so that if one light source independently illuminates an area by 300 lx, while another source illuminates the same area by 200 lx, the illuminance in that area would increase by 500 lx when illuminated by both light sources at the same time [12]. There is also a linear relationship between the illuminance at two different points illuminated by the same source. So if two areas are at 500 lx and 200 lx caused by light from the same source, at 100% power, then those areas would respectively be at 250 lx and 100 lx when the light source is at 50% power. This relationship can be used to quite accurately estimate the illuminance in one area using measurements from another area, when both are illuminated by the same source, and no other light sources illuminate any of those areas.

That light is linear might seem un-intuitive since changes in illuminance do not appear to be linear to the human eye. This is due to the fact that the eye perceives illuminance logarithmically. The illuminance span that the human eye can see in is actually very large, from 0.05 lx, a clear night with full moon, to $32000 - 100000\,lx$, a clear day with direct sunlight, which gives a grasp of how large the span actually is.

2.1.1 Light regulations

This raises the question, what are the requirements for illuminance in offices? According to both the previous and proposed next light level standard in the European Union, EN 12464-1:2002[13] and prEN 12464-1:2019[14], illuminance is supposed to be 500 lx at a standard office working station. The same standards also states that illuminance in non-workspace office areas should be at least 300 lx. These values will be guidelines for the rest of the thesis.

2.1.2 Detectability of changes in illuminance

Weber's law describes that the just noticeable difference in any physical stimulus is proportional to the initial stimuli, according to the following formula:

$$\delta S = SK \tag{2.1}$$

where δS is the just noticeable difference from the initial stimuli S, K is a constant. According to a study of just noticeable difference in illuminance done in [15] the just noticeable difference for illuminance is 7.4%, the experiment was performed in the illuminance region of $100 - 500\,lx$. This means that any changes in illuminance below 7.4% of the initial illuminance will be unnoticeable to most people, even when looking for it. The just noticeable difference will henceforth be referenced to as JND. The same study also found that the difference from a reference illuminance that most people accepted as being equal was between 17.8% and 19.1%. This was found by having the test subjects control a dimmable light and instructing them to tune it to a visible reference illuminance.

2.1.3 Luminaries and how to control them

One of the most common light sources used is the LED (light emitting diode). This is due to the fact that LED lighting is very energy efficient and cheap, it is also fully dimmable. LED lighting is therefore what is used in this thesis.

LED lights can be dimmed in several ways but all the methods are based upon reducing the total input energy and thus reducing the emitted light. One simple method for DC supplied LEDs is to reduce the voltage and current going through the lamp. This is a cheap and simple solution but it has the downside of giving unreliable and uneven results, especially if several LEDs are serially connected. There are therefore a number of other ways to dim LED lighting supplied with either AC or DC.

Forward Phase Control is a method of dimming lights supplied with AC that is based upon cutting off part of the sine wave delivered, thus reducing the total amount of energy delivered to the system. Sine wave dimming can also be used and is based upon reducing the amplitude of the supplied AC. Lights supplied with DC can be dimmed using Pulse Width Modulation (PWM), which is done by alternating the voltage/current between a on/off state resulting in less power to the lights. These methods have the advantage of giving a reliable output, even if there are many LEDs on the same driver. Both of these methods work by reducing the amount of energy that the system receives and thus reducing the emitted light. This is in basis a linear dependence but many LED drivers instead use a quadratic or exponential dimming curve. This is done to better match how light is perceived by the human eye since the human eye's perception of light is logarithmic, an exponential dimming curve will therefore appear to change the light linearly by a human observer.

2.1.4 Daylight modelling

There are models for describing how daylight changes during a day. In this thesis CIE standard overcast sky model [16] will be used:

$$L_\theta = L_z \frac{(1 + 2 sin\theta)}{3}$$

where L_θ is the daylight luminance when the sun is at angle θ from the horizon, and L_z is daylight luminance when the sun is at zenith. This model will be used to create standard profiles for daylight to test the different control systems developed in this thesis.

2.1.5 Effects of dimming on LED lifespan

According to [17] the lifespan of LEDs are affected by the temperature of the diode and the ambient temperature around it among other things. Ways of determining the lifetime of LED lights is an active field of research that is continually expanding. The basis is that one does not measure the time until total failure but usually the time it takes to reach 70% of initial luminance. The main problem with the field is the fact that LEDs have a very long lifetime, at least up to 10 000 hours which means that a normal test of the lifetime is hard to conduct. Usually methods for reducing the lifespan in a controlled way is implemented. [17] furthermore references a test conducted on several LED lights of a major brand that survived at least 25 000 hours active at an ambient temperature of $45°C$. It was found that some of the lights remained operational after 40 000 hours with a potential final lifetime of over 100 000 hours [18]. This would indicate that the energy saved in reduced production by increasing the lifespan of LEDs trough dimming is probably negligible in comparison to the energy saved in decreased energy consumption throughout its use. Especially considering that the largest energy consumption throughout a LEDs lifetime is during use as long as the LED lasts longer than 1 000 hours [19].

2.2 Control theory

Several different controllers will be implemented in this thesis. Initially a SISO controller will be implemented. This will be done in the form of a I-controller but other controllers are also evaluated. Further along the project MIMO controllers in the shape of LQR, LQI and linear programming controllers will be implemented, MPC and constrained LQR is also investigated.

2.2.1 State space models

State space models is a way to describe systems in a intuitive and easy way while also enabling them to be used efficiently. They can be divided into two parts: the output vector and the state vector. These are described as the following:

$$\dot{\mathbf{x}}(\mathbf{t}) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t)$$
$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) \tag{2.2}$$

where $\mathbf{x}(t)$ is the states, $\mathbf{A}$ is how the states $\mathbf{x}(t)$ affects the rate of change of the states, $\mathbf{B}$ is how the input $\mathbf{u}(t)$ affect the states. $\mathbf{y}(t)$ is the outputs of the system, $\mathbf{C}$ and $\mathbf{D}$ is how the states and inputs respectively affect the outputs.

2.2.1.1 Model for controlling illuminance at sensor

The most basic model for a lighting system is:

$$\mathbf{x}(t) = \mathbf{l}(t) + \mathbf{d}(t)$$

where $\mathbf{x}(t)$ is the illuminance on the sensors, $\mathbf{l}(t)$ is the illuminance contribution from the lamps on the sensors and $\mathbf{d}(t)$ is the daylight illuminance contribution on the sensors. As described previously, the relationship between the output of the lamps and their illuminance contribution on the sensors is linear, therefore:

$$\mathbf{x}(t) = \mathbf{B}\mathbf{o}(t) + \mathbf{d}(t) \tag{2.3}$$

where $\mathbf{o}(t)$ is the output of the lamps, it can for example be lamp power, luminous flux or dim level if the dimming curve is linear. The $\mathbf{B}$ matrix is the linear connection between the lamp outputs and their illuminance contribution at the sensors, it can for example be in lx/w, lx/lm or $lx/dim\,level$. In order to control this system with a microcontroller it is discretised, which simply becomes:

$$\mathbf{x}_k = \mathbf{B}\mathbf{o}_k + \mathbf{d}_k$$

where k is a discrete time step. In order to come to the standard form of a discrete state space model, $\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k$, the input to the system, $\mathbf{u}_k$, is defined as the lamp output set by the controller from the measurement of $\mathbf{x}_k$. This gives a state space model of the form:

$$\mathbf{x}_{k+1} = \mathbf{0}_{n\times n}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k + \mathbf{d}_k \tag{2.4}$$
$$\mathbf{y}_k = \mathbf{I}_{n\times n}\mathbf{x}_k \tag{2.5}$$

where $\mathbf{y}_k$ is the illuminance measurements, n is the number of sensors. The $\mathbf{B}$ matrix has shape $n \times m$ where m is the number of controllable lamps. Using this model for control therefore means that the output of the controller is the total lamp outputs, calculated from the measurements at time step k. In addition, with this model the total amount of daylight illuminance present at the sensors is considered a step disturbance.

There is another state space model of interest. This model can be retrieved from the derivative of the sensor illuminance. Equation 2.3 is therefore differentiated with respect to time, which gives:

$$\dot{\mathbf{x}}(\mathbf{t}) = \mathbf{B}\dot{\mathbf{o}}(\mathbf{t}) + \dot{\mathbf{d}}(\mathbf{t})$$

Using Euler's method for discretisation:

$$\frac{\mathbf{x}_{k+1} - \mathbf{x}_k}{\Delta t} = \mathbf{B}\frac{\mathbf{o}_{k+1} - \mathbf{o}_k}{\Delta t} + \frac{\mathbf{d}_{k+1} - \mathbf{d}_k}{\Delta t}$$

A standard form state space model for the system can then be retrieved by defining the input to the system as $\mathbf{u}_k = \mathbf{o}_{k+1} - \mathbf{o}_k$:

$$\mathbf{x}_{k+1} = \mathbf{I}_{n\times n}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k + \Delta\mathbf{d}_k \tag{2.6}$$

$$\mathbf{y}_k = \mathbf{I}_{n\times n}\mathbf{x}_k \tag{2.7}$$

where $\Delta\mathbf{d}_k = \mathbf{d}_{k+1} - \mathbf{d}_k$. A controller based on this model will therefore output the change in lamp output each time step. The illuminance from daylight and illuminance from lamp light is also accumulated in the states $\mathbf{x}_k$ each time step, so the only disturbance is the change in daylight between time steps which can normally be considered white Gaussian with small amplitude, assuming a small enough sampling time. Note that the total amount of daylight is always positively biased.

2.2.1.2 Model for controlling illuminance at ground level

As the illuminated area of interest is the workspace, while the illuminance measurements are taken in the ceiling, a model is needed for the illuminance at ground level. The illuminance at any point on the ground can, just like at the sensors, be described as a combination of illuminance from the lamps and illuminance from daylight. Using this, the two models described in the previous section are also valid for controlling the illuminance at ground level, the difference being that n now is the number of points on the ground where the illuminance is controlled, and that $\mathbf{x}_k$ is the illuminance at these points on the ground instead of the illuminance at the sensors. The problem here is that $\mathbf{x}_k$ is not measured, a state estimator is therefore needed to estimate the illuminance at the ground points from the knowledge of the lamp outputs and sensor measurements. The inspiration for this estimator was the model used in [9]. Assuming that the $\mathbf{B}$ matrix is known, only the daylight component of the ground illuminances is unknown. The daylight illuminance at each ground point is estimated as some linear combination of the daylight illuminance at the sensors:

$$\hat{\mathbf{y}}_{\mathbf{d},\mathbf{k}} = \mathbf{M}(\mathbf{m}_k - \mathbf{G}\mathbf{o}_k)$$

where $\hat{\mathbf{y}}_{\mathbf{d},\mathbf{k}}$ is the estimated illuminance from daylight at the ground points at time step k, $\mathbf{M}$ estimates the daylight illuminance at the ground points as a linear combination of the daylight illuminance at the sensors. $\mathbf{m}_k$ are the sensor measurements for time step k, denoted $\mathbf{y}_k$ in the state space model of the previous section. $\mathbf{o}_k$ is the total output of the lamps and $\mathbf{G}$ is the $\mathbf{B}$-matrix from the state space model in the previous section. The total illuminance at the chosen ground points can then be estimated as:

$$\hat{\mathbf{y}}_{\mathbf{k}} = \hat{\mathbf{y}}_{\mathbf{d},\mathbf{k}} + \mathbf{B}\mathbf{o}_k = \mathbf{M}(\mathbf{m}_k - \mathbf{G}\mathbf{o}_k) + \mathbf{B}\mathbf{o}_k$$

2.2.1.3 Noise modelling

The disturbance affecting the system is daylight and/or other external light sources. Sensor noise is also a part but is considered too small in this application to be relevant.

External light affecting the illuminance is what daylight harvesting uses to save energy. This is light coming mostly from the sun but can also be from external sources such as uncontrolled lamps, lamps in different rooms shining in through doors, computer screens and similar. This noise has a rate of change that is for most cases assumed to be slow. The only case where it is not slow is when something quickly blocks light entering the system. On top of the slow change in light levels there exists a Gaussian component which can be seen in 2.2.

Thus for modelling purposes daylight can be divided in two components; one slowly changing positively biased component, and one approximately zero centred white Gaussian component. For a clearer picture see figures 2.1 and 2.2 where plots can be seen of measurements taken in an office between 08:00 and 17:00 without artificial light present.

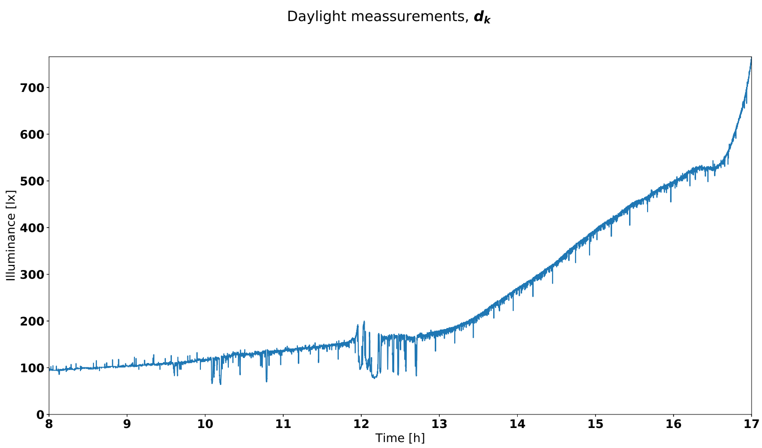

Figure 2.1: Daylight measurements taken between 08:00 and 17:00 in an office with no artificial light.

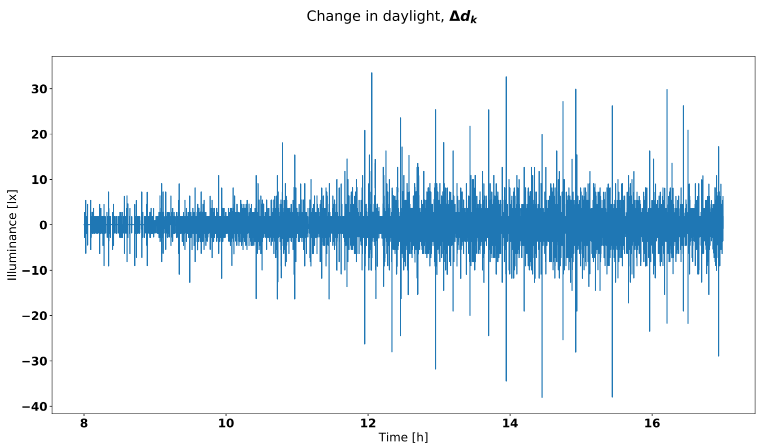

Figure 2.2: The change between measurements in daylight.

As shown in figures 2.1, the total amount of daylight present is slowly changing troughout the day. Meanwhile, as figure 2.2 shows, the changes in daylight second to second is best described as Gaussian. These second to second changes are most likely due to fluctuations in daylight illuminance and not sensor noise, see figures 2.3 and 2.4 which shows plots of measurements taken in front of a lamp outputting a constant amount of light.

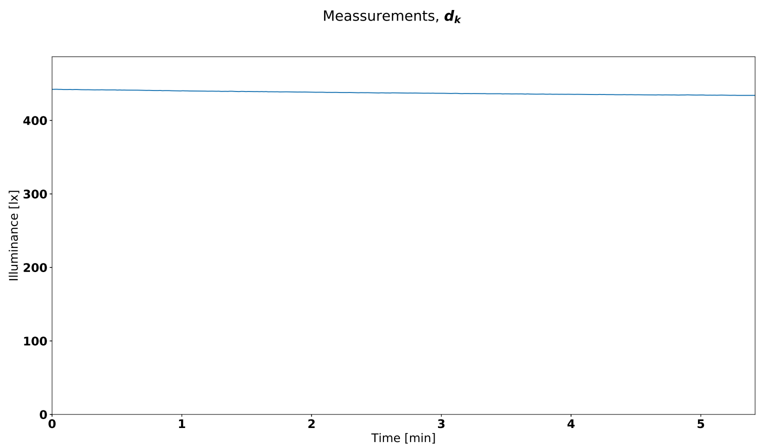

Figure 2.3: Measurements taken with the same sensor, when a lamp is outputting a constant light on the sensor.

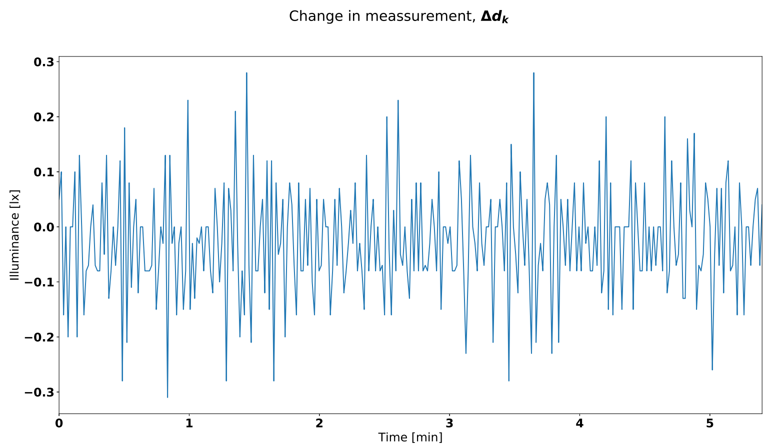

Figure 2.4: The change between measurements.

As shown in figure 2.4, the sensor noise is much smaller than the fluctuations in daylight seen in figure 2.2.

2.2.2 SISO controller

SISO (single input-single output) controllers control systems with one input and output. These controllers are among the most common used and comes in many forms, but the most common are P, PI and PID controllers.

2.2.2.1 Control structure

All controllers have a similar architecture with the main difference being in what form the controller uses the output from the system. Usually the system has the shape shown in fig. 2.5.

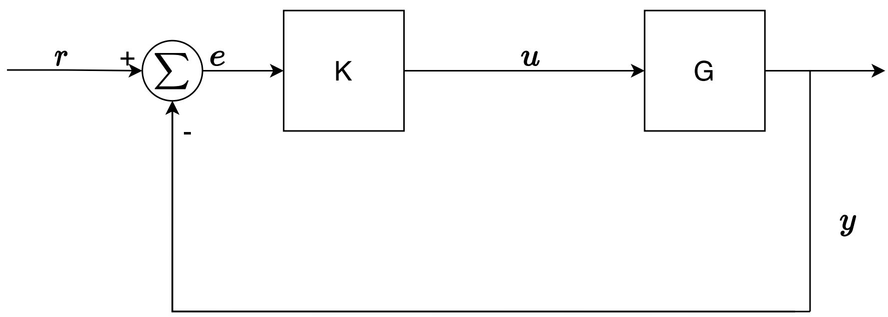

Figure 2.5: The standard control architecture

In figure 2.5, G is the plant/system, y is the output, in this case the sensor readings, r is the reference setpoint, the desired illuminance. e is the error, the difference between the setpoint and the measured output. K is the controller, see the following sections for information on different controller architectures.

2.2.2.2 P controller

The P controller is a simple feedback controller with a proportional gain k_p. The gain is usually determined either though modelling and/or by doing an iterative process. Or if a model is lacking or deemed to be insufficient by a fully iterative tuning method. The controller is described as:

$$u(t) = k_p e(t) \tag{2.8}$$

where $u(t)$ is the input to the system at time t, k_p is the gain, and $e(t)$ is the error from the setpoint at time t. $e(t) = y(t) - r$, where $\hat{y}(t)$ usually is the measurement of the output and r is the setpoint, i.e. the desired output.

2.2.2.3 PI controller

A PI controller is a P controller which also takes previous errors into account. This gives an increased performance and error rejection as well as the possibility to handle static errors and can be defined as:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt \tag{2.9}$$

where k_i is the integration gain. The integral assures that for a well tuned controller the error will go towards zero over time. A too large integration component can however lead to unstable oscillations. Furthermore the integral component enables the system to handle static disturbances better since the integral part does not disappear once the error becomes 0. This is the most commonly used controller.

2.2.2.4 PID controller

A PID controller is a PI controller that also takes rate of change into account. This decreases the potential overshoot of the controller and usually results in a better performance at the cost of a more complex controller and is in the shape of:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{2.10}$$

where k_d is the derivative gain. The derivative part acts as a dampener on the controller, slowing it down if the rate of change of the output becomes too large. However, if there is a large amount of measurement noise the derivative gain can amplify this. This makes the controller slightly slower but also helps with preventing oscillations.

2.2.3 MIMO controller

2.2.3.1 Control structure

The control structure is similar to the structure in the SISO case except for the fact that the model no longer has one input and output but many. Matrices are therefore used in the model instead of scalar values.

2.2.3.2 LQR

A linear quadratic regulator (LQR) is a controller that similar to a P-regulator sets the control output based on the feedback of the system [20]. But in contrast the value is calculated based on the solution to the optimisation problem:

$$min\ \mathbf{J} = \int_{t_0}^{\infty} \mathbf{x}(t)^\top \mathbf{Q}\mathbf{x}(t) + \mathbf{u}(t)^\top \mathbf{R}\mathbf{u}(t) \tag{2.11}$$

The solution to this equation can be found by solving the corresponding algebraic Riccati equation

$$\mathbf{A}^\top \mathbf{P}(t) + \mathbf{P}(t)\mathbf{A} - (\mathbf{P}(t)\mathbf{B})\mathbf{R}^{-1}(\mathbf{B}^\top \mathbf{P}(t)) + \mathbf{Q} = 0 \tag{2.12}$$

resulting in the optimal control policy

$$\mathbf{K} = \mathbf{R}^{-1}(\mathbf{B}^\top \mathbf{P}(t)) \tag{2.13}$$

Or for the discrete case, by solving the corresponding discrete algebraic Ricatti equation:

$$\mathbf{P} = \mathbf{A}^\top \mathbf{P}\mathbf{A} - (\mathbf{A}^\top \mathbf{P}\mathbf{B})(\mathbf{R} + \mathbf{B}^\top \mathbf{P}\mathbf{B})^{-1}(\mathbf{B}^\top \mathbf{P}\mathbf{A}) + \mathbf{Q} \tag{2.14}$$

This is the infinite horizon Ricatti equation, which gives the optimal discrete control policy

$$\mathbf{K} = (\mathbf{R} + \mathbf{B}^\top \mathbf{P}\mathbf{B})^{-1}(\mathbf{B}^\top \mathbf{P}\mathbf{A}) \tag{2.15}$$

The controller has two tuning parameters, **Q** and **R**, which are usually diagonal matrices containing penalty factors, **Q** penalises the square error between the states and the setpoint, while **R** penalises the control action. The reason for the name infinite horizon is because the equation can iteratively be solved starting with $\mathbf{P} = \mathbf{Q}$ and stepping through it until the **P** value stabilises thus resulting in the shape described in 2.14

Bryson's rule is a good starting point to find suitable initial **Q** and **R** values and is described as:

$$q_{i,i} = \frac{1}{(largest\ acceptable\ error\ for\ state\ i)^2} \tag{2.16}$$

$$r_{j,j} = \frac{1}{(largest\ acceptable\ error\ for\ input\ j)^2} \tag{2.17}$$

These might need to be manually tuned afterwards but are potentially sufficient and will otherwise give a good initial value.

2.2.3.3 LQI

A linear quadratic integrator is a linear quadratic regulator where the controller also takes the sum of all setpoint errors into account [21]. This is done by redefining the system as shown in figure 2.6.

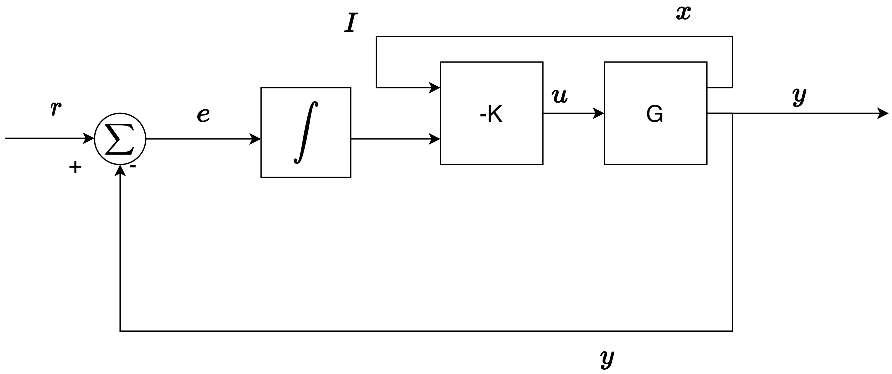

Figure 2.6: Layout of a LQI

an augmented **A** and **B** matrix is therefore constructed that also takes the sum of previous errors into account resulting in the following matrices

$$\mathbf{A}_{LQI} = \begin{bmatrix} \mathbf{A} & \mathbf{0} \\ -\mathbf{C} & \mathbf{I} \end{bmatrix} \tag{2.18}$$

$$\mathbf{B}_{LQI} = \begin{bmatrix} \mathbf{B} \\ \mathbf{0} \end{bmatrix} \tag{2.19}$$

It might be necessary to constrain the integral states to prevent so called integral wind-up.

2.2.3.4 Constrained LQR and model predictive control

Constrained linear quadratic regulators (CLQR) works in a similar way to a regular LQR with one major difference. Since constraints are introduced, the discrete algebraic Riccati equation no longer has a static solution and will potentially change for each time step. This means that the control gain **K** will no longer have one optimal value but will change depending on the position of the input and state space.

To solve this problem the system is instead considered to be a quadratic optimisation problem with the following shape:

$$\begin{aligned} min\, \mathbf{J} = \mathbf{x}\mathbf{Q}\mathbf{x}^\top + \mathbf{u}\mathbf{R}\mathbf{u}^\top \\ s.t \\ \mathbf{x}^+ = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{h}(x,u) = 0 \\ \mathbf{g}(x,u) \leq 0 \end{aligned}$$

Where $\mathbf{h}(x,u)$ and $\mathbf{g}(x,u)$ are expressions of constraints for the states **x** and inputs **u**. This problem can for example be solved using Quadprog in Matlab or a similar solver. The complexity of the controller increases but the input and states can be bounded in the solution.

Model Predictive Control (MPC) is similar to a CLQR with one major difference. Instead of doing one control step, the optimisation is instead done over several simulated control steps and minimise the total control sum while also ensuring that the constraints are not broken in any of the steps. Then using the first control step each iteration. This comes at the cost of an increase in the number of variables for each time step (linear) and an increase in the size of the matrices that are needed to describe the problem (quadratic). All this leads to an increase in the memory required to solve the problem as well as an increase in calculation time. Due to the fact that a quadratic solver usually has a cost increase per variable of around n^3 this means that the hardware requirements on the solver is quite high since it requires alot of memory and computational power.

2.2.3.5 Linear programming - the simplex algorithm

The simplex algorithm in linear programming is a tool to obtain an optimal solution to a linear optimisation problem consisting of an objective function, to be either maximised or minimised, and a set of linear constraints. In this thesis all constraints used will be of the form: $\sum_i a_i x_i \leq b$, $b \geq 0$, where a_i and b are constants, while x_i is a decision variable. Therefore only the specific form of the simplex algorithm used to solve such problems is described here. Before starting the simplex algorithm, the objective function and the constraints are converted into a Simplex tableau, consisting of a **A**-matrix, **b**-vector, and **c**-vector. Note that the **A**-matrix and **b**-vector has nothing to do with the **A** and **B** matrices in the models desribed previously, this is simply the standard defintion of the simplex tableau. The **A**-matrix contain the coefficients of each decision variable for each constraint, the **b**-vector contain the constants of each constraint, and the **c**-vector contains the coefficients of each decision variable in the objective function. This is done by adding so called slack variables to each constraint to turn them into equalities. For example:

$$
\begin{aligned}
max\ z = 2x_1 + x_2 \\
s.t \\
2x_2 \geq x_1 - 2 \\
2x_1 + x_2 \leq 3
\end{aligned}
$$

$$
\begin{aligned}
max\ z - 2x_1 - x_2 = 0 \\
s.t \\
x_1 - 2x_2 + s_1 = 2 \\
2x_1 + x_2 + s_2 = 3 \\
\mathbf{A} = \begin{bmatrix} 1 & -2 & 1 & 0 \\ 2 & 1 & 0 & 1 \end{bmatrix} \\
\mathbf{b} = [2 \quad 3]^\top \\
\mathbf{c} = [-2 \quad -1 \quad 0 \quad 0]
\end{aligned}
$$

The simplex algorithm then works in the following way:

- Identify the column in **c** with the most negative value, if all values are positive the optimal solution has been found. This column is known as the pivot column. In the example above this would be column 1.

- Identify the row in **A** with the smallest ratio of $\frac{b_i}{a_{i,c}}$ where $a_{i,c} \geq 0$, i is the row and c is the pivot column identified in the previous step. This row is known as the pivot row. In the example above this would be row 2, as $\frac{3}{2} < \frac{2}{1}$

- Identify pivot value as $a_{r,c}$ where r is the pivot row and c is the pivot column. In the example above this value would be 2.

- Divide all values on the pivot row in **A** and **b** by the pivot value. In the example above the new pivot row would be: $[1 \quad 0.5 \quad 0 \quad 0.5]$, and the value of the pivot row in the **b**-vector would become 1.5.

- Eliminate all values on the pivot column, except for the pivot row, by adding/-subtracting multiples of the pivot row to each row. In the example above, the new **A**-matrix would become: $\begin{bmatrix} 0 & -2.5 & 1 & -0.5 \\ 1 & 0.5 & 0 & 0.5 \end{bmatrix}$, and the new **b**-vector would become: $[0.5 \quad 1.5]^\top$

- Eliminate any value on the pivot column in **c** by adding/subtracting multiples of the pivot row. In the example above the new **c**-vector would become: $[0 \quad 0 \quad 0 \quad 1]$

- Repeat from step 1 until all elements in **c** are positive. In the example above the solution would be found after 1 step, as all elements in **c** are positive, the solution looks like:

$$\mathbf{A} = \begin{bmatrix} 0 & -2.5 & 1 & -0.5 \\ 1 & 0.5 & 0 & 0.5 \end{bmatrix}$$
$$\mathbf{b} = [0.5 \quad 1.5]^\top$$
$$\mathbf{c} = [0 \quad 0 \quad 0 \quad 1]$$

- Identify the values of the variables by finding all pivot columns, and then identifying the corresponding pivot row for each pivot column. The value of the variable corresponding to the pivot column is the value in the **b**-vector corresponding to that pivot row. Each variable that does not have a pivot column is 0. In the example above, the solution would be: $[x_1 \quad x_2 \quad s_1 \quad s_2] = [1.5 \quad 0 \quad 0.5 \quad 0]$ meaning that the solution to the original problem is: $x_1 = 1.5,\ x_2 = 0$

3

Methods

3.1 Measurements and how to measure light

For measuring illuminance a Lux sensor from Adafruit, TSL2591 is used. This sensor is capable of measuring illuminance between 188 $\mu lx - 88\, klx$, depending on the setting, [22]. This is well within office illuminance levels. The accuracy of the illuminance measurements can be changed with the integration time used to get the average illuminance level. This can be set between 100 and 600 ms. This in combination with an ESP32 Pico kit and a standard sampling time of 1 Hz forms the basis for the controllers used.

3.2 SISO controllers

This section describes the construction and implementation of SISO controllers used in this thesis.

3.2.1 SISO controller for controlling illuminance at sensor

During initial testing a controller was developed for a simple SISO system, where the lux sensor was placed directly on the surface of interest. This meant that the illuminance measurements directly corresponded to the illuminance in the area of interest. The desired behaviour of the controller was that it would not change its output too rapidly, while also being able to follow natural variations in ambient light closely. P-, PI-, and PID-controllers were initially considered, but the controller that performed by far the best for this task was an I-controller with adaptive gain and a deadband of 15 lx:

$$k_i = \begin{cases} 0.2 & |r-y| < 40\, lx \\ 0.1 & otherwise \end{cases}$$

$$u^+ = \begin{cases} u + k_i(r-y) & |r-y| > 15\, lx \\ u & otherwise \end{cases}$$

where k_i is the control gain for the current time step, r is the desired illuminance, y is the currently measured illuminance, and u is the illuminance contribution from the lamp at the sensor which is the sum of the previous control inputs. u^+ is the desired illuminance contribution from the lamp at the sensor for the next time step. Note that setting $k_i = 1$ means that the controller theoretically reaches the setpoint in one step, this is not done due to the desired behaviour being that the controller does not change its output too rapidly. The deadband of 15 lx was introduced to prevent the controller from oscillating between two dim levels, as the dim levels are integers, while the true optimal dim level can be a decimal number leading to oscillation between the two nearest integer dim levels. In order to transform u^+ into a dim level to be used for the lamp, a calibration step has to be done. The calibration step involves measuring the illuminance when the lamp is at full power, and when it is turned off, then taking the difference between these two illuminances to get how much illuminance contribution at the sensor the lamp achieves at maximum power. Then in order to convert the desired illuminance contribution to a dim level, the dimming curve function for the lamp can be used, it connects the dim level with the lamp power, the lamp in question is controlled with DALI, which uses a standardised function for the connection between dim level and lamp output [23]:

$$L(d) = 10^{(d-1)\frac{3}{253}} \frac{L_{100\%}}{1000} \qquad 1 \leq d \leq 254 \tag{3.1}$$

where $L(d)$ is the lamp power at dim level d, and $L_{100\%}$ is the lamp power at full output. Since the lamp power increases the luminous flux of the lamp linearly, and the illuminance at the sensor also increases linearly with the luminous flux, the lamp power can be substituted for the illuminance contribution of the lamp at the sensor:

$$u(d) = 10^{(d-1)\frac{3}{253}} \frac{u_{100\%}}{1000} \qquad 1 \leq d \leq 254 \tag{3.2}$$

where $u(d)$ is the illuminance contribution from the lamp at the sensor at dim level d, and $u_{100\%}$ is the illuminance contribution from the lamp at the sensor at full power, which is measured in the calibration step. This function can easily be inverted in order to get dim level as a function of illuminance contribution from the lamp at the sensor:

$$d(u) = \frac{253}{3} log_{10}\left(1000 \frac{u}{u_{100\%}}\right) + 1 = \frac{253}{3} log_{10}\left(\frac{u}{u_{100\%}}\right) + 254 \qquad 10^{-3} \leq \frac{u}{u_{100\%}} \leq 1 \tag{3.3}$$

3.2.2 SISO controller for controlling workspace illuminance

In order to make the previous controller be able to control light in a certain workspace, while the sensor being used is placed in the ceiling, a model for approximating the illuminance at the workspace from the illuminance at the ceiling is necessary. This is done using a calibration step, where a separate lux sensor is used to measure the illuminance in the workspace when the lamps are at full power, and when they are turned off. Measurements are also taken at the ceiling sensor. The estimation of the workspace illuminance is done as the SISO version of the estimation described in section 2.2.1.2. The daylight illuminance at the workspace is therefore estimated as the daylight illuminance at the sensor multiplied with some constant. The illuminance from lamp light at the workspace is the illuminance from lamp light at the sensor multiplied with another constant. The model for retrieving the illuminance in the workspace is therefore:

$$
\begin{aligned}
\hat{y}_d &= C_d(m - u) \\
y_l &= C_l u \\
\hat{y} = \hat{y}_d + y_l &= C_d(m - u) + C_l u
\end{aligned}
$$

where $\hat{y}_d$ is the estimated daylight illuminance at the workspace, m is the sensor measurement, y_l is the illuminance from lamp light at the workspace, $\hat{y}$ is the total estimated illuminance at the workspace. u is the illuminance contribution from the lamps at the sensor. C_l and C_d are the constants that respectively translates lamp illuminance and daylight illuminance from sensor to workspace. These constants are retrieved in the following way during the calibration step:

$$
C_l = \frac{y^{100\%} - y^{0\%}}{m^{100\%} - m^{0\%}} \tag{3.4}
$$

$$
C_d = \frac{y^{0\%}}{m^{0\%}} \tag{3.5}
$$

where $y^{j\%}$ is the measurement from the workspace when the lamps are at $j\%$ power. $m^{j\%}$ is the ceiling sensor measurement when the lamps are at $j\%$ power. The same controller instead controlling the illuminance at the workspace indirectly trough measurements at the ceiling then becomes:

$$
k_i = \begin{cases} 0.2 & if|r - \hat{y}| < 40\, lx \\ 0.1 & otherwise \end{cases}
$$

$$
u^+ = \begin{cases} u + k_i \frac{r-\hat{y}}{C_l} & if|r - \hat{y}| > 15\, lx \\ u & otherwise \end{cases}
$$

the division with C_l is done to translate the error in illuminance at the workspace, to how much the illuminance contribution from the lamps at the sensor need to be increased in order to eliminate any error at the workspace, so that u can still be the illuminance contribution from the lamps at the sensor. The dim level to set the lamps at time step k is then retrieved, just like in the initial controller trough Eq. (3.3)

The controller was implemented using three 3290 lm light armatures and one Adafruit TSL2591 lux sensor for the control. An extra sensor was used to calibrate the system and measure the workspace illuminance for reference. The room for the system was approximately 12 m^2, allowing for a theoretical maximum illuminance of 822.5 lx in the room from only the artificial light.

3.3 Evaluation of SISO controllers

Once a good SISO controller was found it was evaluated.

3.3.1 Controller property test

A test of the performance of the SISO controller was conducted. It is described in this section.

3.3.1.1 SISO controller for controlling illuminance at the sensor

The SISO controller for controlling illuminance at the sensor is evaluated by running the controller on a lamp facing a sensor on a desk in an office. The disturbance affecting the controller is daylight entering trough the office windows.

3.3.1.2 SISO controller for controlling illuminance at workspace

The SISO controller for controlling illuminance at workspace level is evaluated over a period of several months in a small office with a roof mounted sensor and microcontroller. The office has windows facing to the west, meaning that most daylight will be available in the afternoon. A reference sensor is placed on a workspace (approximately 1 meter above the ground) both for calibrating the system and for measuring the true workspace illuminance for reference. The room is occupied by two engineers during ordinary office hours. The occupants are able to turn the control on/off and change the setpoint of the controller for ergonomic reasons. This allows for feedback on the performance of the controller, as well as verification on how accurate the acceptable illuminance difference from section 2.1.2 is. Data is logged from the controller and reference workspace sensor every minute. The occupants also give feedback on the system.

3.3.2 SISO controller energy savings test

The initial plan for calculating the energy savings of the SISO controller was to run it with a setpoint of $500\,lx$ over the duration of a workday with good weather. This would yield a number for the relative energy savings of the controller during a day with a large amount of daylight available. However, the communication bus between the ceiling mounted SISO controller and the luminaries broke down before this was done, and there was not enough time to fix it during this thesis. Luckily there was a large amount of data logged from the performance of the controller over several months while it was working, however, the setpoint of the controller was set by the occupants of the room to a lower value, meaning that the energy savings of the controller for a setpoint of $500\,lx$ cannot be retrieved directly. Instead, the constant relation between the illuminance contribution of the lamps at the sensor, and their contribution at the workspace, described in section 3.2.2, is used to extrapolate the lamp output the controller would have set if the setpoint had been $500 lx$ throughout a chosen workday with partly cloudy weather at the end of April from 08:00 to 17:00.

This extrapolation is carried out in the following way, for each discrete time step of the controller throughout the chosen day:

$$\hat{u}_{k,500\,lx} = \begin{cases} C_l u_k + 500 - s_k & u_k > 0 \\ max(0, 500 - s_k) & u_k = 0 \end{cases}$$

where $\hat{u}_{k,500\,lx}$ is the extrapolated illuminance contribution the controller would have achieved at the workspace if the setpoint at time step k had been $500\,lx$. C_l is the constant ratio between illuminance contribution at the sensor and illuminance contribution at the workspace of the lamps, described in section 3.2.2. u_k is the controller output at time step k, the illuminance contribution at the sensor the controller achieves at time step k. s_k is the setpoint of the controller at time step k, which can be changed by the occupants of the office. Note that when the controller has turned the lamps off, perfect control is assumed in the extrapolation, while when the lamps are being controlled, the control is simply scaled to the new setpoint. This scaling is not exactly true to reality either, as the controller in reality would control less aggressively than the scaled up control signal had the setpoint been at $500\,lx$. The relative energy saved by the extrapolated controller throughout the chosen day is then calculated as:

$$E_{\%\,saved} = 100\left(1 - \frac{\sum_{k=1}^{n} \hat{u}_{k,500\,lx}}{500n}\right)$$

where n is the number of discrete time steps throughout the chosen day. This gives the relative energy saved by the extrapolated controller in comparison to an uncontrolled system which permanently outputs $500\,lx$ illuminance contribution at the workspace.

A simulation of the SISO controller is also done on a daylight profile used to test the potential energy savings of the MIMO controllers, described in section 3.7.2. The calibration of the controller is assumed to be perfect in this simulation to give the best approximation of potential energy savings. As imperfect calibration would either give an under- or overestimation of the workspace illuminance which respectively gives a lower and higher energy savings of the controller. This gives an approximation of how much energy the SISO controller would save under the same daylight profile as the MIMO controllers are tested on. Energy savings is also compared to a system where the lamps are turned off when enough daylight is present at the workspace.
Combining these two tests it is possible to get decent a approximation of the energy consumption and potential savings of the SISO system.

3.4 The MIMO system

A miniature physical test rig for testing of the MIMO controllers is constructed as a $0.5 \times 0.5 \times 0.25\,m$ box using 24 white frosted LED lights, and 5 lux sensors of the type Adafruit TSL2591 placed in the roof of the box. Furthermore screens are fitted to the sensor to limit the region that they measure most of the light from to the deflections from the ground below each sensor. This is done so that the measurements from the sensors is more correlated with the illuminance at the ground below the sensors. In contrast to the SISO system, the LEDs now have a linear dimming curve, which means that the luminous flux of the lamps increase linearly with the dim level. The LEDs are dimmed with PWM, with dimming levels between 0 and 4095, with 0 being completely off and 4095 being fully on.

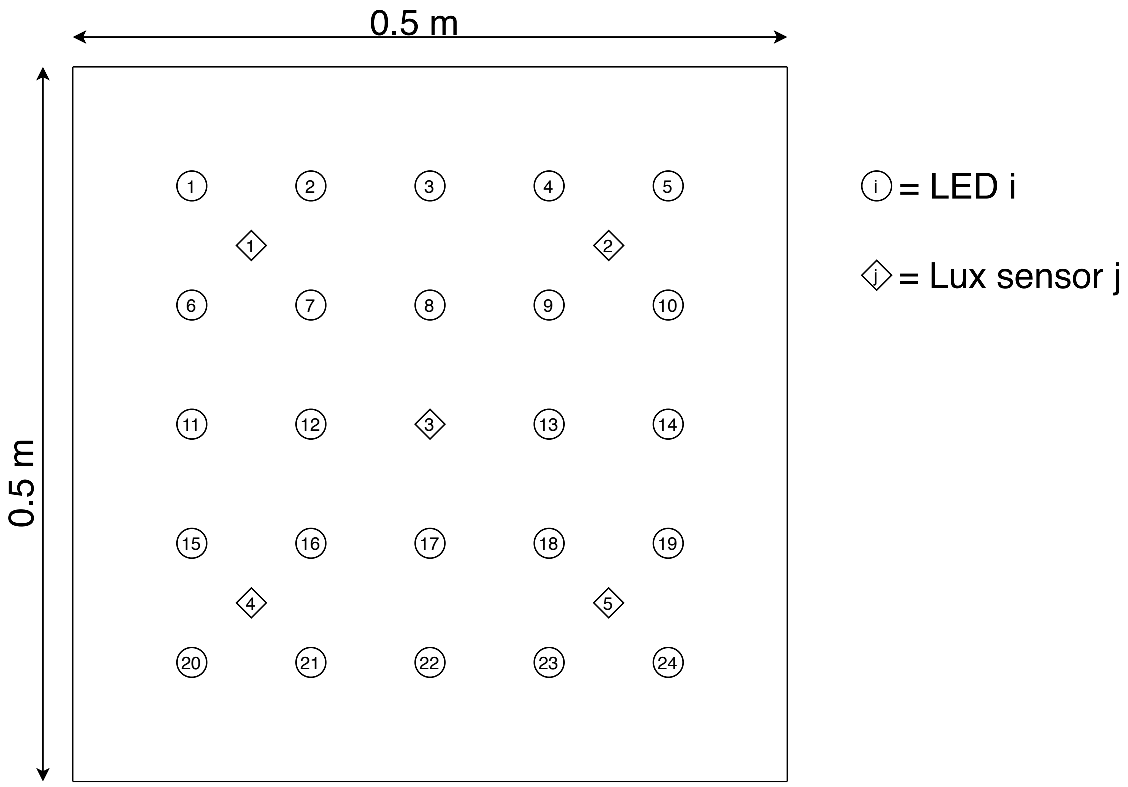

Figure 3.1: A sketch of the MIMO system with the numbering of the lamps and sensors

On the side of sensors 4 & 5 the wall is replaced with a strip on the top to allow for disturbance light to enter the system.

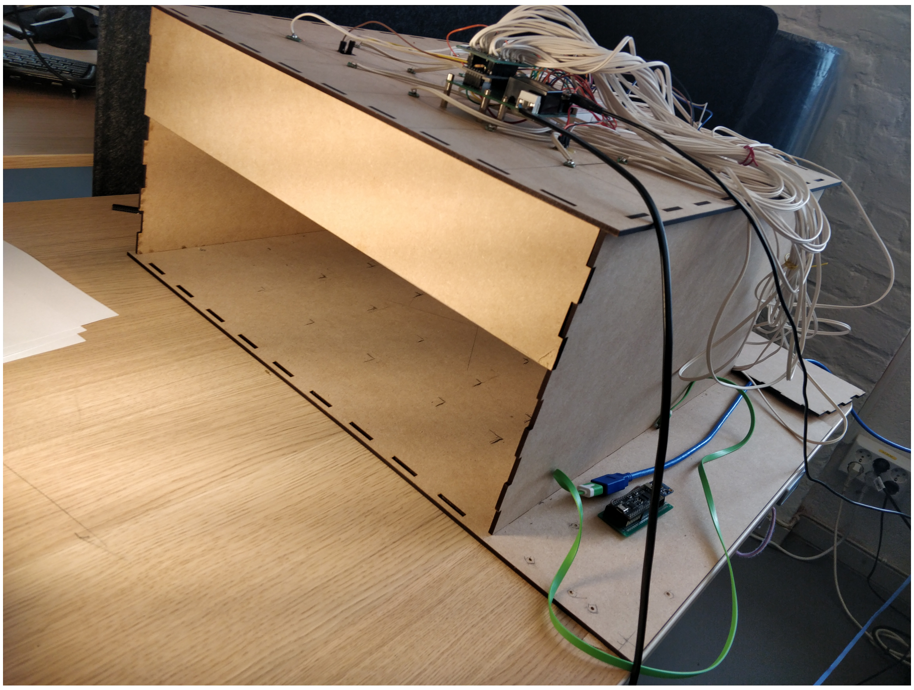

Figure 3.2: Front of the MIMO system with the opening for disturbance light

Figure 3.3: Inside of the MIMO system, with the LEDs visible, the sensors are placed inside the cardboard screens

A lamp is placed outside the box facing the side with the top strip mounted on it, this lamp acts as a disturbance source.

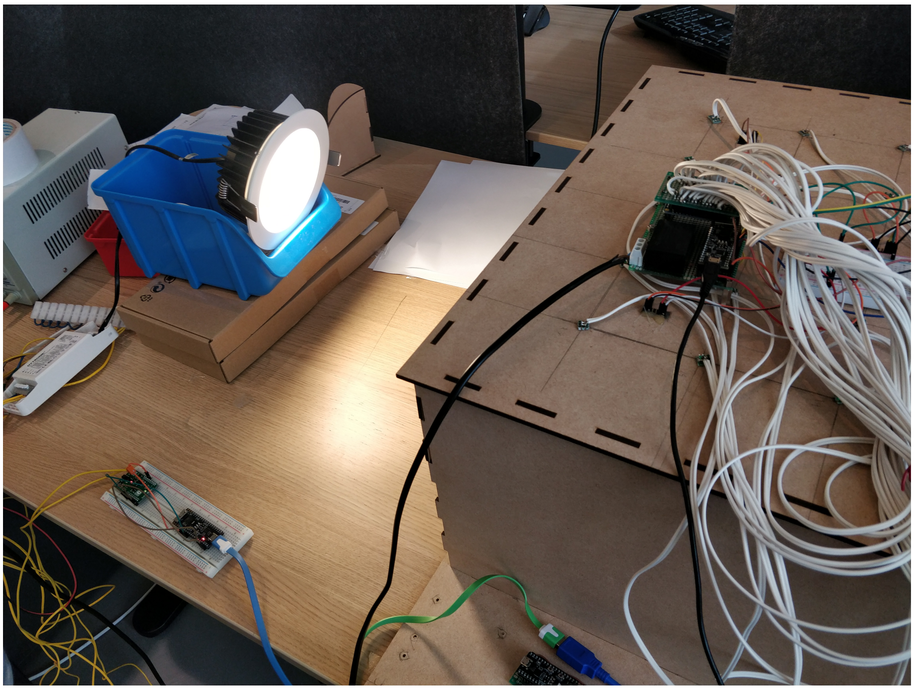

Figure 3.4: The disturbance lamp shining into the MIMO system

This system enables repeated test with identical light disturbances thus giving a good performance metric. The highest illuminance achievable on the ground in some corners is just above 200 lx. This means that the controllers of the system do not utilise a setpoint of 500 lx but instead use a setpoint of 200 lx. Potential relative energy savings of the controllers developed for this system can still be estimated by scaling down the disturbance to $\frac{2}{5}$ of what it would have been for a full scale lighting system.

3.5 MIMO controllers, controlling illuminance at the sensors

MIMO controllers are constructed first to control directly on the sensor illuminance and then further along to control illuminance at the ground.

3.5.1 Constructing the B matrix

The elements of the **B** matrix can be found by turning the lamps on one-by-one and reading the sensor measurements to find each lamp's effect on each sensor. However, initial testing found this approach to give unreliable results. A simplified model for the general appearance of the **B** matrix is therefore constructed instead. An illustration of this model looks like:

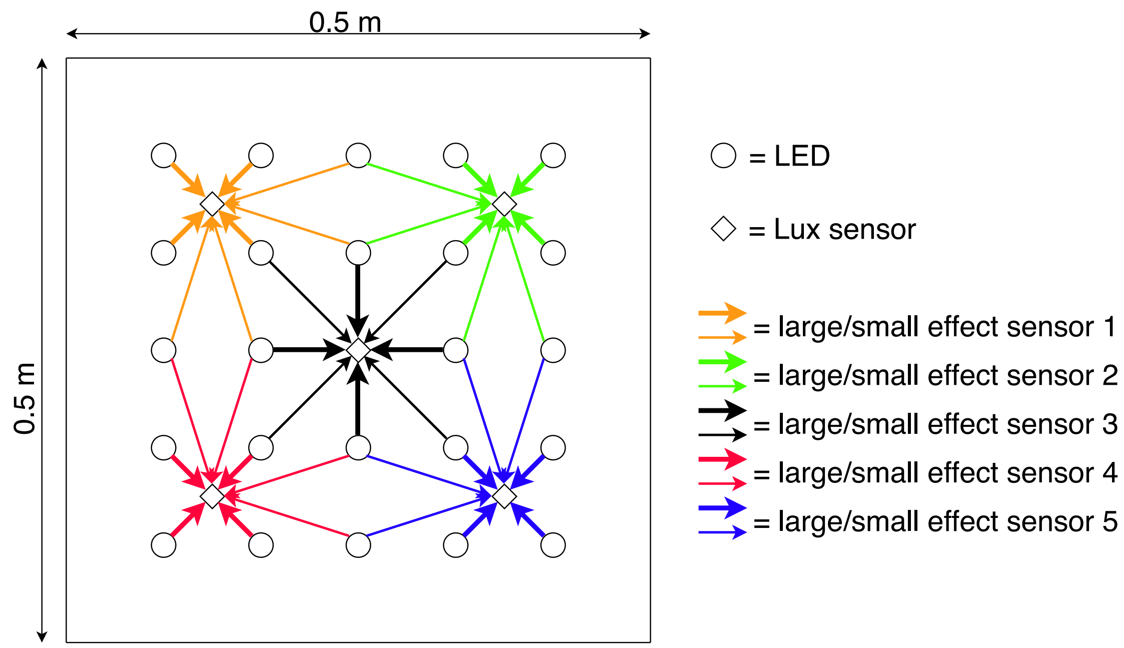

Figure 3.5: An illustration of the **B** matrix for controlling illuminance at sensors, i.e how much each lamp affects the reading of each sensor

The **B** matrix is constructed according to figure 3.5, where each thick arrow represents a value of double the size of a thin arrow of the same colour, except for sensor 3 where the thick arrows are $\frac{4}{3}$ the size of the thin arrows. This model was constructed as it was noted that when building the **B** matrix automatically it usually had roughly this shape. Only five values then have to be found: the value of the thin arrows of each colour. These are found in practice by turning the lights to a reference dimming vector $\mathbf{d}^*$ and reading the measurements of each sensor, a measurement is also taken with the lights off so that the ambient light can be removed from the measurements. The values are then found as:

$$
\begin{aligned}
b_{i,low} &= \frac{y_i^{d^*} - y_i^{0\%}}{2\sum_{j\in H_i} d_j^* + \sum_{j\in L_i} d_j^*} \qquad i \neq 3 \\
b_{i,high} &= 2b_{i,low} \qquad i \neq 3 \\
b_{3,low} &= \frac{y_3^{d^*} - y_3^{0\%}}{\frac{3}{4}\sum_{j\in H_i} d_j^* + \sum_{j\in L_i} d_j^*} \\
b_{3,high} &= \frac{4}{3} b_{i,low}
\end{aligned}
$$

Where $y_i^{d^*}$ is the measurement of sensor i when the lights are at the reference dimming vector, $y_i^{0\%}$ is the measurement of sensor i when the lights are off, $b_{i,low}$ is the value of the thin arrows for sensor i in figure 3.5 while $b_{i,high}$ is the value of the thick arrows for sensor i. H_i is the set of all lamps connected with a thick arrow to sensor i in figure 3.5, L_i is the set of all lamps connected with a thin arrow to sensor i. This approach means that the elements of the **B**-matrix are in $lx/dim\,level$, this works since the dimming curve for the lamps is linear, meaning that an increase of 1 dim level will always increase the luminous flux of the lamps by a set amount.

3.5.2 Decoupled controller

The decoupled controller is one independent SISO controller for each sensor, controlling the dim level of the nearby lights. It was decided that such a controller should be tested. The SISO controller used is the same the architecture controller as described in section 3.2.1, except that the gain is not adaptive, and no deadband is implemented, as the dim levels are of a higher resolution in the MIMO system. The gain is set to 0.5, as this controller can be more aggressive. The MIMO system was therefore divided into five zones, one for each sensor. These zones envelop the lights nearest to the sensor of that zone. The controller calculates a dim level independently for each zone, just as in the SISO case. However, some zones overlap meaning that some lights are located in more than one zone. The dim levels of those lights are therefore set to the average dim level of all the zones it occupies.

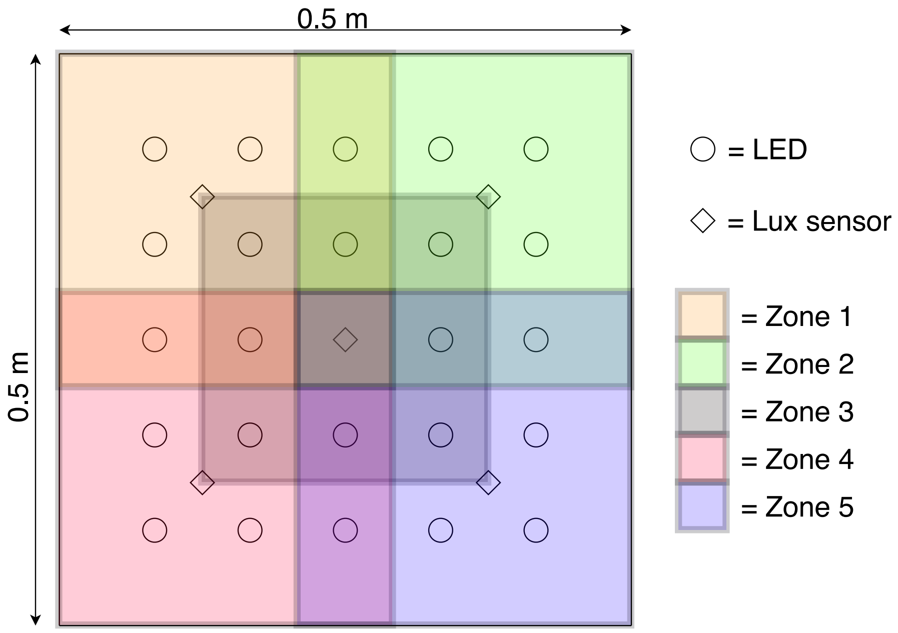

Figure 3.6: The zones of the 5 independent SISO controllers

3.5.3 LQR

The LQR controller is constructed according to 2.2.3.2 with $\mathbf{A} = \mathbf{I}_{5\times5}$ with the $\mathbf{B}$ matrix created according to 3.5.1. The choice of $\mathbf{A}$ gives the controller an internal integral effect that enables it to handle daylight disturbances. The weightings of the $\mathbf{Q}$ and $\mathbf{R}$ matrices are tuned to give a heavy focus on minimising the state error as primary focus while also trying to keep inputs within the allowed control span. The control gain was calculated in Matlab and simulated to find a suitable tuning. Once a control gain performed well in simulation it was tested on the real system.

3.5.4 LQI

LQI controllers were created according to 2.2.3.3 for both $\mathbf{A} = \mathbf{0}_{5\times5}$ and $\mathbf{A} = \mathbf{I}_{5\times5}$ with the $\mathbf{B}$ matrix created once again according to 3.5.1. Both controllers are created and tested in Matlab. They are tuned to have a high penalty on the state error. A method to handle integral windup was implemented according to:

$$I_{err} \in [I_{low},\ I_{high}] \tag{3.6}$$

with I_{low} and I_{high} values found by a combination of an iterative process and an analysis of the integral values at different parts of the simulation. The goal of the anti-windup was to give a good performance from the integral while removing the effect of integral windup due to large daylight illuminances that could not be compensated for, while still enabling good performance from the integral. For $\mathbf{A} = \mathbf{0}_{5\times5}$ it was found that the lowest acceptable value was 0, and the highest value was 4095, as the total dim level is controlled and the integral acts as the steady state value for the dim levels, but for $\mathbf{A} = \mathbf{I}_{5\times5}$ the value depended on the acceptable rate of change and could thus be negative.

3.5.5 CLQR and MPC control

Due to constraints in the memory size of the ESP32 microcontroller as well as time constraints it will not be possible to implement these kind of controllers on the physical system. But they will be tested in simulation and compared to simulated performance of the LQR/LQI controllers. This is due to the complexity of creating a online quadratic solver for the optimisation problems and the size of the required matrices. The tests of these controllers will be conducted by simulating a LQR, a MPC and a constrained LQR controlling the sensor illuminance in Matlab and then comparing their results. Since the LQR is tested on the real system it will be possible to extrapolate information about the constrained LQR:s and MPC:s possible performance on the real system.

3.5.6 Hand-tuned regulator

Due to behaviour noticed in testing of the LQR it was found that finding a controller that could perform well in the constrained range of the control output might be problematic. Thus a "hand-tuned" regulator is created where a custom gain matrix is used, based upon the **B** matrix. This controller has the same shape as the LQR but the control gain is instead defined as:

$$\mathbf{K} = k\mathbf{B} \tag{3.7}$$

where k is a tuning parameter which changes the aggressiveness of the controller. The advantage of this controller is that, since all elements in the gain matrix are positive, no dim levels will be changed in the wrong direction as compared to the error between measurement and setpoint. Instead, each dim level will be changed proportionally to how large of an effect the specific lamp has on the measurement error.

3.5.7 LP-controller

The problem of minimising the dim level of all lamps while maintaining a certain illuminance can be described as a linear programming problem. It was therefore decided that a controller based on this should be tested. Before setting up the LP-problem some constants are defined:

d : *dim rate, highest allowable change in dim level from previous level*
δ : *highest allowable difference between neighbouring lamps*
N_i : *Set of all neighbouring lamps of lamp i*
r : *Global setpoint for sensors*
a_i : *max dim level for lamp i, following dim rate, and* $d \leq 4095$
r_j : *sensor j setpoint, set so that it is always achievable*
u_i : *Dim level of lamp i*
y_j : *Illuminance measurement from sensor j*

$$a_i = \begin{cases} u_i + d & if\ u_i + d < 4095 \\ 4095 & otherwise \end{cases}$$

$$r_j = \begin{cases} \sum_{i=1}^{24} b_{j,i}(a_i - u_i) + y_j & if\ \sum_{i=1}^{24} b_{j,i}(a_i - u_i) + y_j < r \\ r & otherwise \end{cases}$$

The constructed LP-problem to solve then becomes:

Decision variables:

u_i^+ : *new dim level for lamp i*

o_j : *allowable overshoot for sensor j*

Problem:

$$min \sum_{i=1}^{24} u_i^+ + 1000 \sum_{j=1}^{5} o_j \qquad s.t:$$

$$\sum_{i=1}^{24} b_{j,i}u_i^+ - \sum_{i=1}^{24} b_{j,i}u_i \geq r_j - y_j \qquad \forall j \in \{1, ..., 5\}$$

$$\sum_{i=1}^{24} b_{j,i}u_i^+ - \sum_{i=1}^{24} b_{j,i}u_i + y_j - r_j \leq o_j \qquad \forall j \in \{1, ..., 5\}$$

$$u_i^+ \leq a_i \qquad \forall i \in \{1, ..., 24\}$$

$$u_i^+ \geq \begin{cases} u_i - d & if\ u_i - d > 0 \\ 0 & otherwise \end{cases} \qquad \forall i \in \{1, ..., 24\}$$

$$o_j \leq \sum_{i=1}^{24} b_{j,i}(a_i - u_i) + y_j - r_j \qquad \forall j \in \{1, ..., 5\}$$

$$u_i^+ \leq u_n + \delta \qquad \forall i \in \{1, ..., 24\}, n \in N_i$$

$$u_i^+, o_j \geq 0 \qquad \forall i \in \{1, ..., 24\}, j \in \{1, ..., 5\}$$

Due to the constrained memory size of the microcontroller used, all neighbour constraints cannot fit into the memory. The set of neighbours is visually shown in figure 3.7.

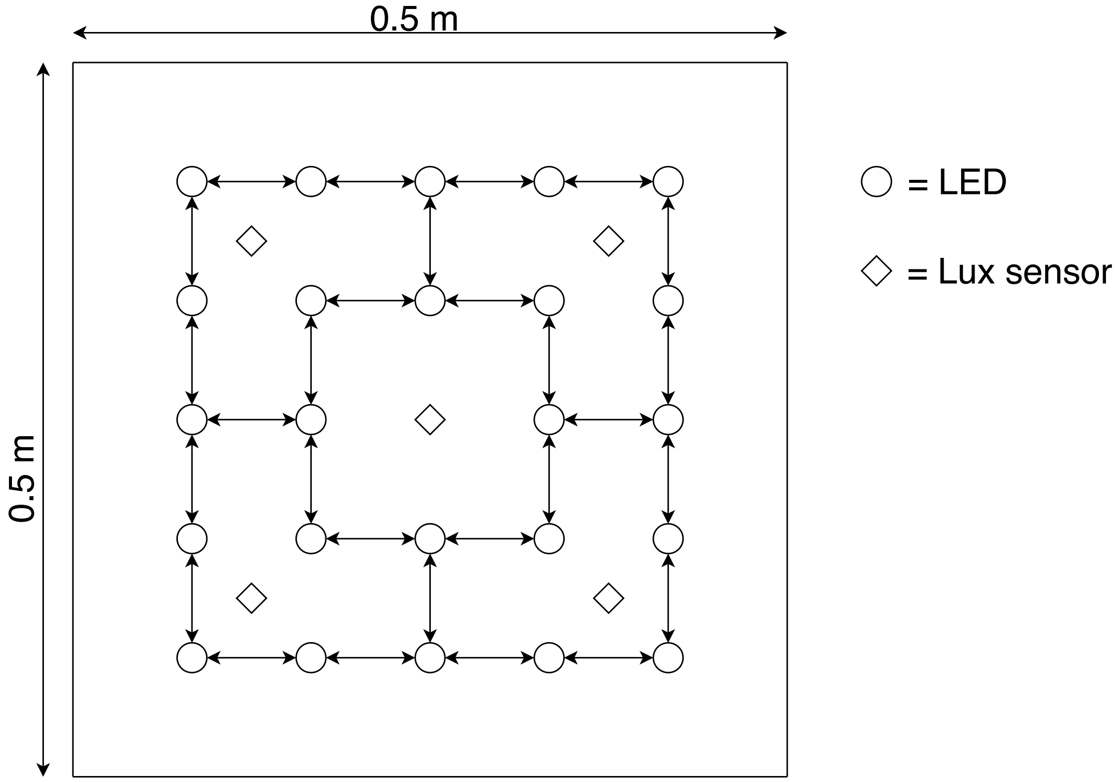

Figure 3.7: Simplified neighbour connections, for a lamp i, every lamp n that has a direct arrow to lamp i is in the neighbour set N_i

To solve this problem with the simplex algorithm, the problem is converted to the form $\mathbf{Ax} \leq \mathbf{b}$, where all elements in $\mathbf{b}$ are positive. For this to be possible a change in decision variables has to be made:

$$\begin{aligned} u_i^+ &= a_i - v_i \\ o_j &= \sum_{i=1}^{24} b_{j,i}(a_i - u_i) + y_j - r_j - c_j \end{aligned}$$

so the new decision variables are now v_i and c_j, with some algebraic manipulation the LP-problem now becomes:

$$max \sum_{i=1}^{24} v_i + 1000 \sum_{j=1}^{5} c_j \qquad s.t: \tag{3.8}$$

$$\sum_{i=1}^{24} b_{j,i} v_i \leq \sum_{i=1}^{24} b_{j,i}(a_i - u_i) + y_j - r_j \qquad \forall j \in \{1, ..., 5\} \tag{3.9}$$

$$c_j - \sum_{i=1}^{24} b_{j,i} v_i \leq 0 \qquad \forall j \in \{1, ..., 5\} \tag{3.10}$$

$$v_i \leq \begin{cases} a_i & if\ u_i - d \leq 0 \\ a_i + d - u_i & otherwise \end{cases} \qquad \forall i \in \{1, ..., 24\} \tag{3.11}$$

$$c_j \leq \sum_{i=1}^{24} b_{j,i}(a_i - u_i) + y_j - r_j \qquad \forall j \in \{1, ..., 5\} \tag{3.12}$$

$$v_i - v_n \leq \delta + a_i - a_n \qquad \forall i \in \{1, ..., 24\}, n \in N_i \tag{3.13}$$

$$v_i, c_j \geq 0 \qquad \forall i \in \{1, ..., 24\}, j \in \{1, ..., 5\} \tag{3.14}$$

In words this LP-problem, in the order above, is:

- 3.8: Objective is to minimise overshoot of the setpoints for all sensors, and dim levels for all lamps, where a decrease of 1000 dim levels is valued as equal to a decrease of 1 lx in overshoot.

- 3.9: For all sensors, the increase in illuminance from lamps is greater than or equal to the error between measurement and setpoint. i.e. the setpoint has to be reached.

- 3.10: For all sensors, the increase in illuminance from lamps is less than or equal to the error between measurement and setpoint plus allowable overshoot of setpoint. i.e. the overshoot of the setpoint is not larger than the allowed overshoot.

- 3.11: For all lamps, the new dim level is greater than or equal to either zero, or the old dim level minus the dim rate, whichever is more constraining.

- 3.12: For all sensors, the allowable overshoot is greater than or equal to zero.

- 3.13: For all lamps, the new dim level is within δ dim levels of the new dim level of all lamps in the lamp's neighbour set.

- 3.14: For all lamps, the new dim level is less than or equal to a_i, i.e the new dim level upholds the dim rate.

- 3.14: For all sensors, the allowable overshoot is less than or equal to the largest possible overshoot that can be achieved at the sensor according to the model.

It might seem redundant to both minimise overshoot and dim level, as logically, minimising the dim level should result in the smallest possible illuminance that still reaches the setpoint. This is however not always the case, as sometimes it can be possible to achieve a lower sum of dim levels by increasing the dim level of some lamp that will reach the setpoint on one sensor, but overshoot the setpoint on another sensor. The reason for the added constraint that neighbouring lamps need to have a similar dim level is that the solution otherwise often consists of maxing a few lamps, while turning off the other lamps, which leads to a very uneven illumination of the ground, which the problem does not otherwise consider.

The actual control loop is shown in figure 3.8.

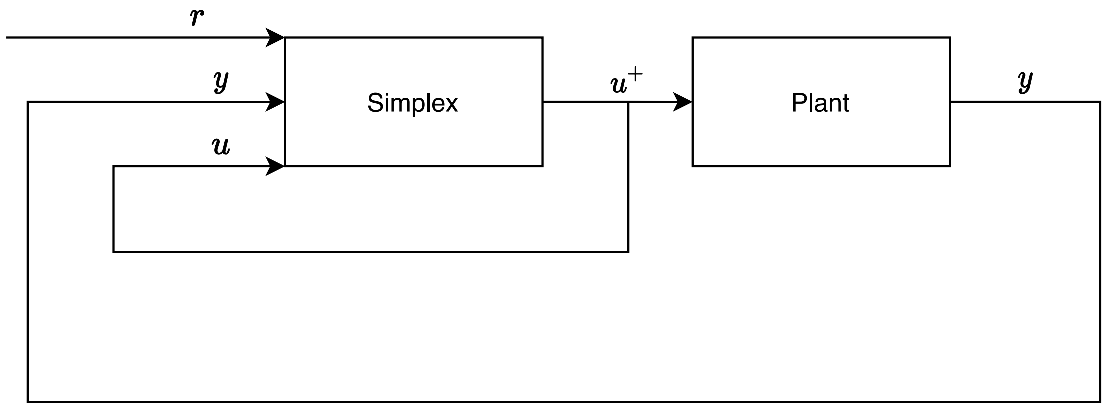

Figure 3.8: The control loop for the LP-controller

The simplex block in figure 3.8 builds a simplex tableau for the LP-problem described above, solves it for the new dim levels using the simplex algorithm, and outputs the new dim levels each time step.

3.6 MIMO controllers, controlling illuminance at ground level

The state space model used in these controllers is described in section 2.2.1.2.

3.6.1 Constructing the M matrix and the new B matrix

The **M** and **B** matrices described in section 2.2.1.2 are both constructed trough manual measurements in the ground zones. The **B** matrix is constructed by putting a sensor in each zone, and then turning on the lamps close to the zone one-by-one to find the effect of each of those lamps on the zone illuminance. The **M** matrix is constructed by having the lamps turned off and measuring the daylight present in each ground zone, and at the ceiling sensors. Each element of **M** is then retrieved as:

$$m_{i,j} = \begin{cases} \frac{y_{g,i}}{y_{s,j}} & \textit{If } j \textit{ is the closest sensor to zone } i \\ \frac{y_{g,i}}{2y_{s,j}} & \textit{If } j \textit{ is one of two sensors equally close to zone } i \\ 0 & \textit{otherwise} \end{cases}$$

Where $y_{g,i}$ is the measurement on the ground in zone i, and $y_{s,j}$ is the measurement of sensor j. For example, looking at the numbering in figure 3.1, one can see that the daylight illuminance in zone 1 will be estimated as $m_{1,1}$ multiplied with the daylight illuminance at sensor 1. The daylight illuminance in zone 3 will be estimated as the sum of $m_{3,1}$ and $m_{3,2}$ multiplied with the daylight illuminance at sensor 1 and 2 respectively, thus the division by two in the equation when two sensors are equally close to a zone. This means that for these zones the estimated daylight illuminance can be viewed as the average of the estimate from two sensors. An illustration of how the daylight illuminance estimation of the zones look like can be seen in figure 3.9.

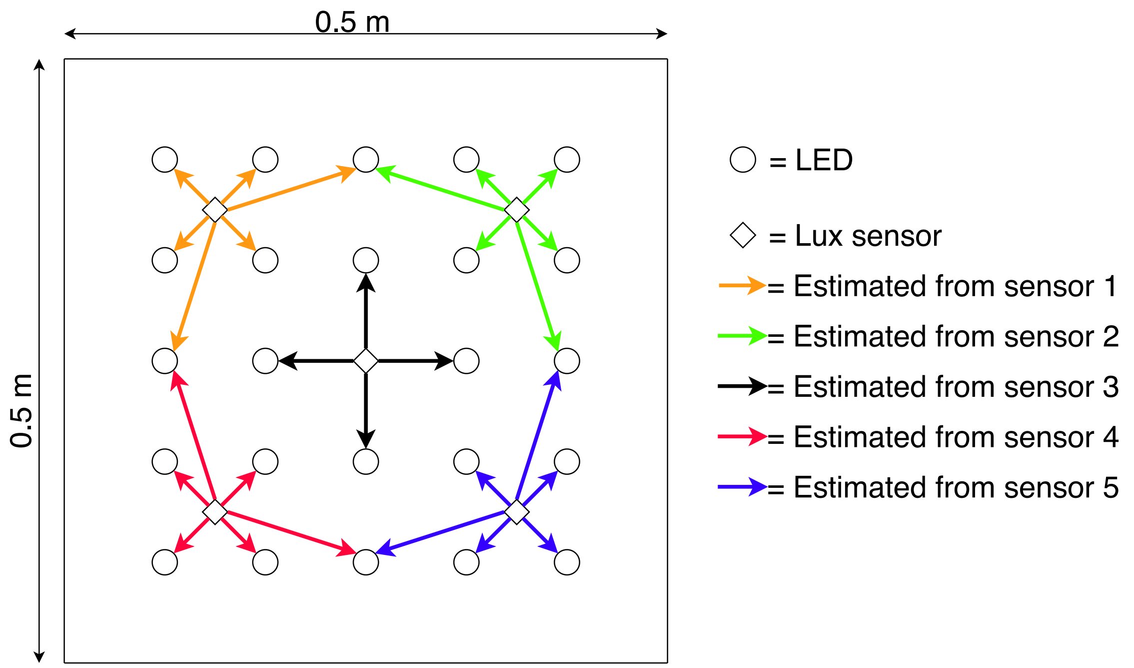

Figure 3.9: Illustration of the M-matrix

3.6.2 LQR for ground Illuminance

A LQR for control of illuminance at ground level is created based on the state space model described in 2.2.1.2. The controller is tuned with a high penalty on the state error. This model includes an estimator of the illuminance at each ground zone, so the new control loop now looks like:

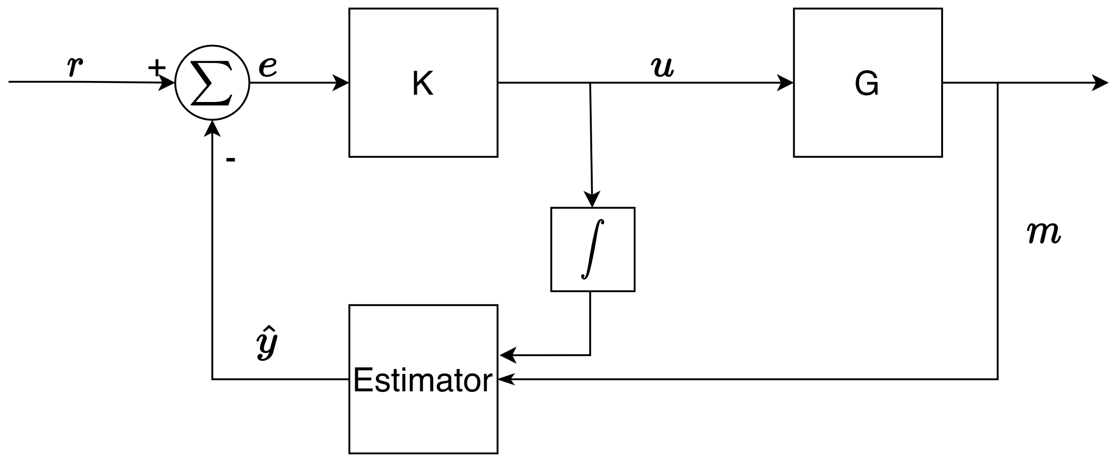

Figure 3.10: Controller architecture for the LQR controlling estimates of the ground illuminances

This controller have for the MIMO system the controller have a calculation time of 4.305 milliseconds for each controller step. On the ESP32 pico controller.

3.6.3 LP-controller

In order to have the LP-controller instead control the illuminance at ground level the measurements are simply substituted for the illuminance level at the zones for all constraints in the LP from 3.5.7 according to the model described in section 2.2.1.2. The constraint that neighbouring lamps need to have a similar dim level is removed, as solving the illuminance constraint in all ground zones in itself leads to even illuminance at ground level. The new LP-optimisation problem then becomes:

$$max \sum_{i=1}^{24} v_i + 1000 \sum_{j=1}^{24} c_j \qquad s.t:$$

$$\sum_{i=1}^{24} b_{j,i} v_i \leq \sum_{i=1}^{24} b_{j,i} a_i + \sum_{n=1}^{5} m_{j,n}(y_n - \sum_{i=1}^{24} g_{j,i} u_i) - r_j \qquad \forall j \in \{1, ..., 24\}$$

$$c_j - \sum_{i=1}^{24} b_{j,i} v_j \leq 0 \qquad \forall j \in \{1, ..., 24\}$$

$$v_i \leq \begin{cases} a_i & if\ u_i - d \leq 0 \\ a_i + d - u_i & otherwise \end{cases} \qquad \forall i \in \{1, ..., 24\}$$

$$c_j \leq \sum_{i=1}^{24} b_{j,i} a_i + \sum_{n=1}^{5} m_{j,n}(y_n - \sum_{i=1}^{24} g_{j,i} u_i) - r_j \qquad \forall j \in \{1, ..., 24\}$$

$$v_i, c_j \geq 0 \qquad \forall i \in \{1, ..., 24\}, j \in \{1, ..., 24\}$$

Note that $b_{i,j}$ is now the elements of the **B** matrix for the state space model described in section 2.2.1.2, $g_{i,j}$ are now the elements of the **G** matrix from section 2.2.1.2, it is the same as the **B** matrix used in the previous LP-controller. j is now the zone number, instead of the sensor number as in the previous LP-formulation. As previously the new dim levels are obtained by:

$$u_i^+ = a_i - v_i \qquad \forall i \in \{1, ..., 24\}$$

The calculation time for this controller is measured to be around 1000 ms with spikes at 1400 ms.

3.7 Evaluation of the MIMO controllers

This section describes the evaluation of the MIMO controllers for both sensor illuminance and ground illuminance.

3.7.1 Controller property test

A light profile is generated based on the light model described in 2.1.4 to test the responsiveness and ability to track the setpoint of the different MIMO controllers. A daylight level is generated for every second of the test, each time step the next daylight level is generated according to the model plus normally distributed noise with standard deviation $\frac{1}{40}$ of the previous daylight level. That the sun gets blocked by clouds is simulated by having a chance of $\frac{1}{200}$ each time step that the sun gets blocked by clouds, or if it is already blocked by clouds the daylight level returns to normal. When the sun is blocked by clouds the daylight level falls by between 20 and 81% randomly and stays at that level until the sun is unblocked. With this algorithm a daylight profile that challenges the controllers with behaviours that can occur during a normal day is generated.

The noise profile used in later tests, generated from this model looks like:

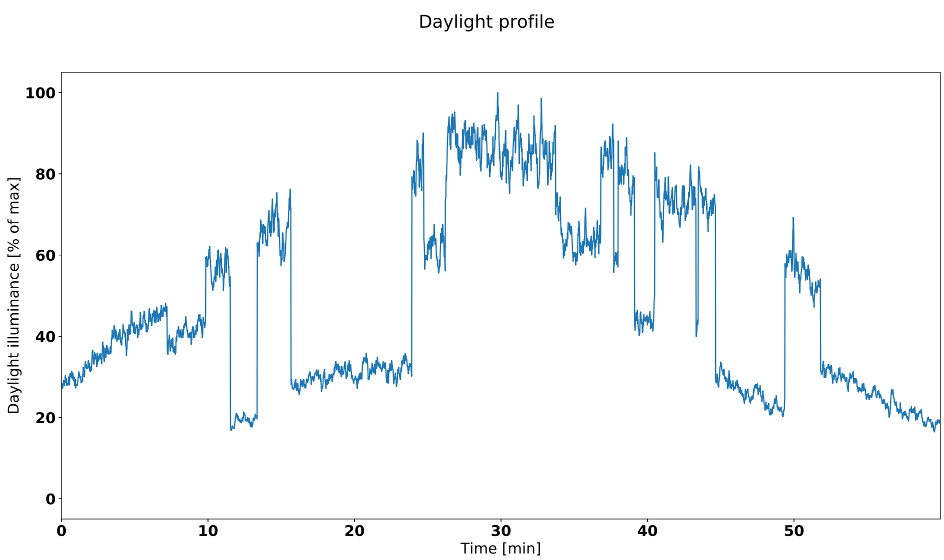

Figure 3.11: The chosen generated daylight disturbance profile

The generated daylight profile is as mentioned earlier introduced into the MIMO system by a separate, stronger lamp, controlled by a separate microcontroller that follows the daylight profile. The lamp is placed outside the box in such a way that it shines into the box trough an opening, in order to make it similar to daylight entering a room trough a row of windows. The light profile tries to approximately match the shape of a semi-clear day compressed to be only 1 hour long.

3.7.1.1 Test for controllers of illuminance at sensors

This test is for the controllers described in section 3.5. For these controllers the setpoint is set at 30 lx. This is due to the fact that the illuminance at the sensors is much lower than the illuminance on the ground. A similar behaviour can be seen in the roof mounted sensor in the SISO system. The different controllers are then evaluated with the noise profile for 1 hour each. The average dim level and the illuminance readings are recorded to study the behaviour of the controller.

3.7.1.2 Test for controllers of illuminance at ground level

This test is for the controllers described in section 3.6. In this test the setpoint is set to 200 lx, the same disturbance profile is used. The test is run by placing a reference sensor in one of the ground zones and running the controller with the disturbance profile. The test is done once for every ground zone and controller. The controller estimates of the ground illuminance, average dim level and sensor measurements are read from the controller during the test, while the true ground zone illuminance is read from the reference sensor.

3.7.2 Controller energy savings test

The potential energy savings of the MIMO controllers is evaluated by simulating a full days performance on a light profile retrieved trough measurements on a workspace in the same office the SISO controller of workspace illuminance is in. This allows the energy savings of the MIMO controllers to be compared to that of the SISO controller. The amplitude of the daylight throughout this test is scaled by $\frac{2}{5}$, as the MIMO system on its own only can reach a ground level illuminance of 200 lx, while the illuminance in an office environment should be 500 lx. The disturbance lamp is programmed such that $\frac{2}{5}$ of the measured daylight illuminance from the daylight profile is added at the centre point of the MIMO system. The test is done over a 9 hour period, corresponding to a workday between 08:00 and 17:00. In the MIMO system the dimming curve of the lamps is linear, meaning that the output of the lamps changes linearly with the dim level. The relative energy savings of the MIMO controllers during the test can therefore be calculated as:

$$E_{\%\,saved} = 100\left(1 - \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} d_j^i}{mnd^*}\right) \tag{3.15}$$

where m is the number of lamps, n is the number of discrete time steps throughout the test, d_j^i is the dim level of lamp j at time step i and d^* is the average dim level the lamps have to be at to achieve a ground level illuminance of 200 lx without daylight. This calculation only work if the controller has a hard control frequency.

Since the LP-controller does not have a hard control frequency, the relative energy savings for it is instead calculated as:

$$E_{\%\,saved} = 100\left(1 - \frac{\sum_{j=1}^{m}\sum_{i=1}^{n}\Delta t(i)d_j^i}{tmd^*}\right) \tag{3.16}$$

where $\Delta t(i)$ is the length of time step i and t is the total duration of the test. This means that $\sum_{i=1}^{n}\Delta t(i) = t$.

4

Results

4.1 SISO Controller, controlling illuminance at sensor

The SISO controller for illuminance at a sensor was tested by controlling a lamp on a desk with a light sensor in front of the lamp on the desk. For the controller architecture see 3.2.1. The test was taken over a 210 minute period in the afternoon on a sunny day to see how well the controller could follow the setpoint.

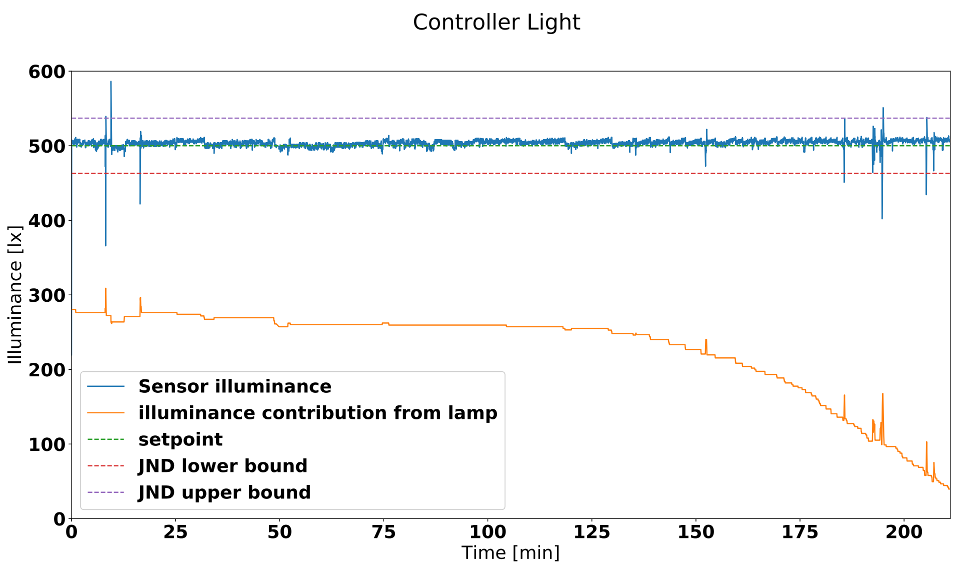

Figure 4.1: SISO controller of illuminance at sensor

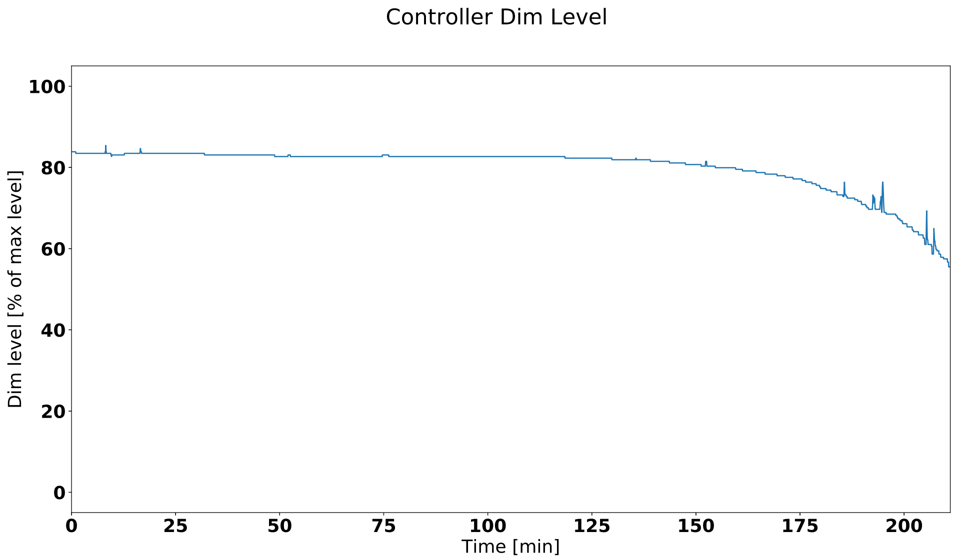

Figure 4.2: The dim levels sent to the lamp over time. Note that the connection between dim level and lamp output is exponential in this application.

as can be seen in figures 4.1 & 4.2 the controller kept the illuminance at the sensor very close to the setpoint. JND in the figure refers to the just noticeable difference from the setpoint, described in section 2.1.2. The large sudden changes in illuminance were due to the daylight being temporarily blocked by objects moving past outside the window as the test was done on the first floor of an office.

4.2 SISO controller, controlling illuminance at workspace

The controller described in 3.2.2 was implemented in a small office occupied by two engineers who had the ability to send commands to the controller, most importantly to turn the control on/off and change the setpoint. Data from the controller and a reference sensor located on the workspace was logged every minute over a period of several months. Plots over a 24 hour period starting at 00:00 and ending at 23:59 in a sunny day in march can be seen in figures 4.3, 4.4 and 4.5.

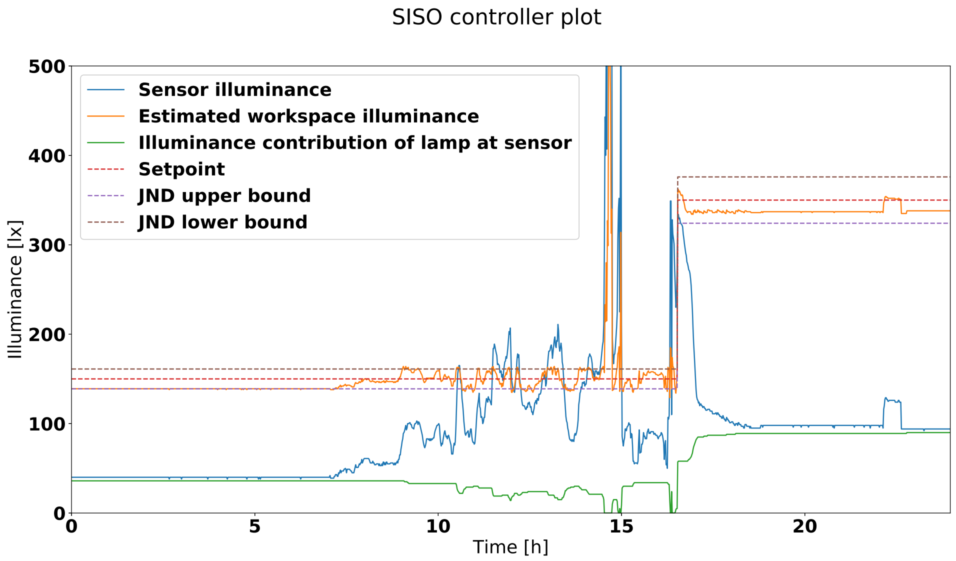

Figure 4.3: A plot of the controller in the ceiling during a 24h period starting at 00:00 and ending at 23:59

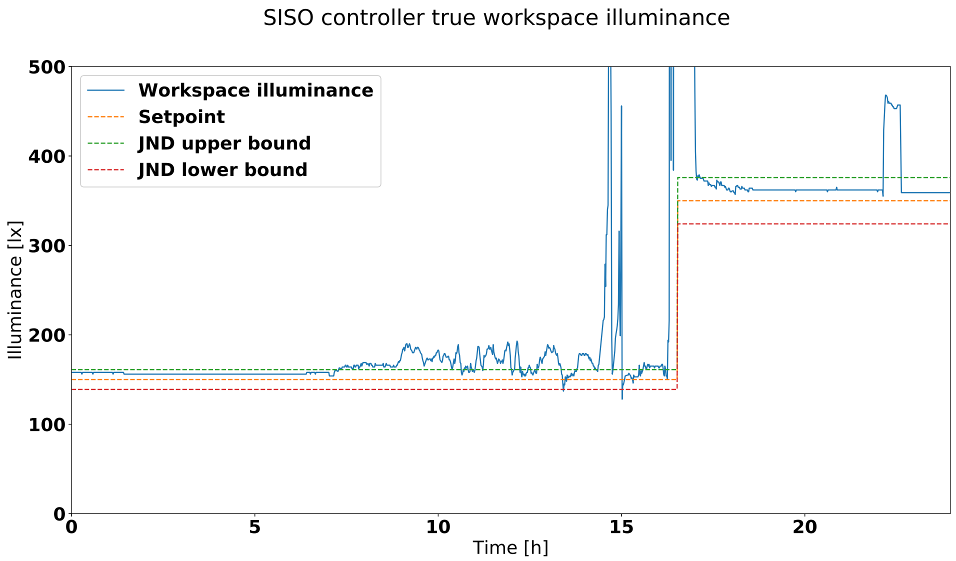

Figure 4.4: Plot of the true illuminance at the workspace over the same 24h period starting at 00:00 and ending at 23:59

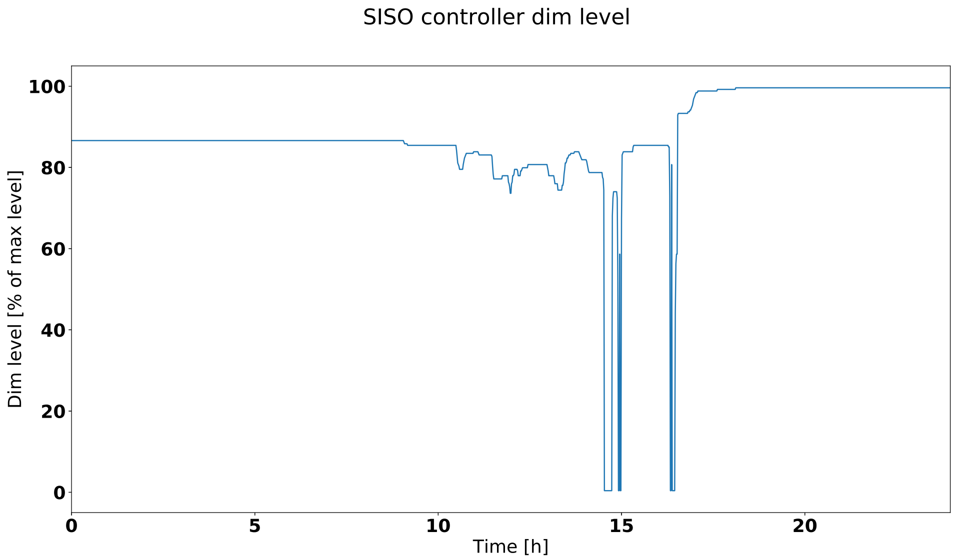

Figure 4.5: Plot of the dim levels sent to the lamps over the same 24h period, note that the connection between dim level and lamp output is exponential in this application.

Figures 4.3, 4.4 and 4.5 shows that the SISO control of illuminance at a workspace worked fairly well. However, the estimation of the illuminance at the workspace was of course not perfect, but was nonetheless fairly accurate such that the true illuminance at the workspace for most of the time was close to being within the just noticeable difference from the setpoint illuminance. For a small period just before 15:00 the daylight illuminance was too large for the controller to reach the setpoint, at this point the lamps were turned off as there is nothing more the controller can do. Also note that the setpoint of the controller was changed from 150 lx to 350 lx by the occupants at 16:32, which is the reason for the lamps output increasing from 0 to approximately 100 lx contribution at the ceiling sensor at that time.

There were several things that was learned from the use of the system in a room where people were working. There was little notice of the controller while it was running. The only case where the occupants noticed the controller was when the dim level was changed from 1 to 0, i.e. when the lamps went from outputting minimum amount of light to being turned off. This might be because the luminaries in question had quite a high lowest lamp output. This was not possible to change as it was a characteristic of the luminaries used, the problem was instead solved by not turning the luminaries off unless the illuminance was far above the setpoint. Furthermore the occupants changed the setpoint from 500 lx to lower values, preferring 150 to 200 lx in the morning and 350 lx in the afternoon.

4.3 Performance tests: MIMO controllers, controlling illuminance at sensors

All architectures for the MIMO controllers of illuminance at sensors are described in section 3.5. The controllers were tested with the same randomly generated daylight profile, the generation is described in section 3.7.1, see figure 4.6 for the profile used.

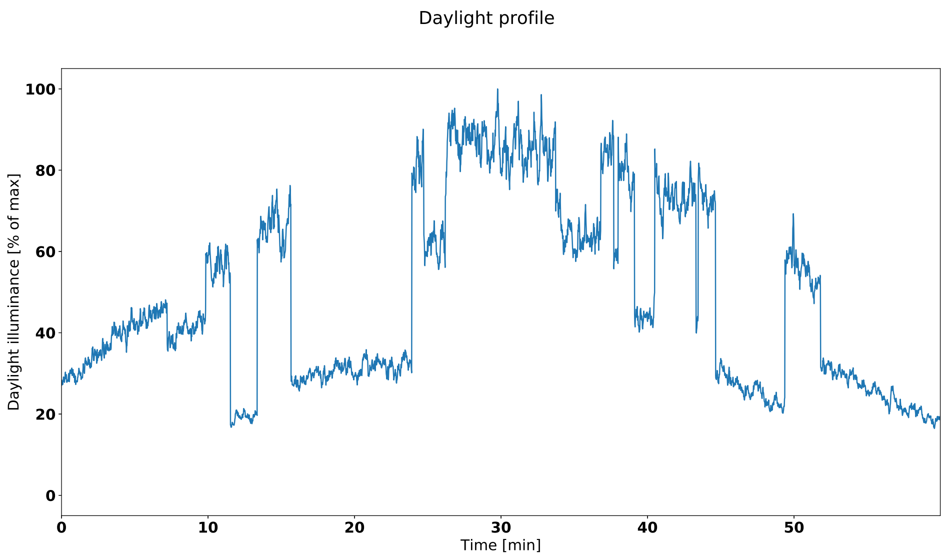

Figure 4.6: The daylight profile to test the MIMO controllers for illuminance at sensors

4.3.1 Decoupled MIMO controller

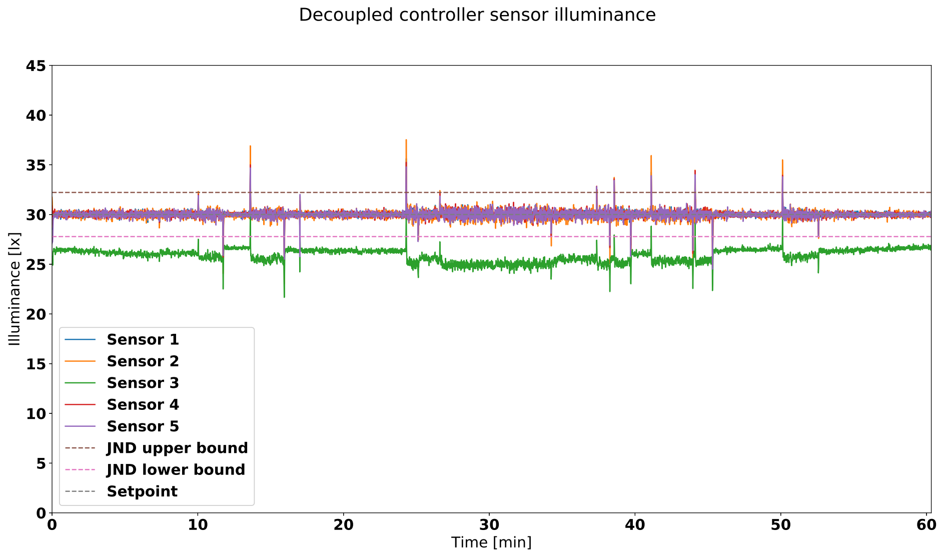

Figure 4.7: The sensor illuminance readings over the duration of the test of the decoupled controller

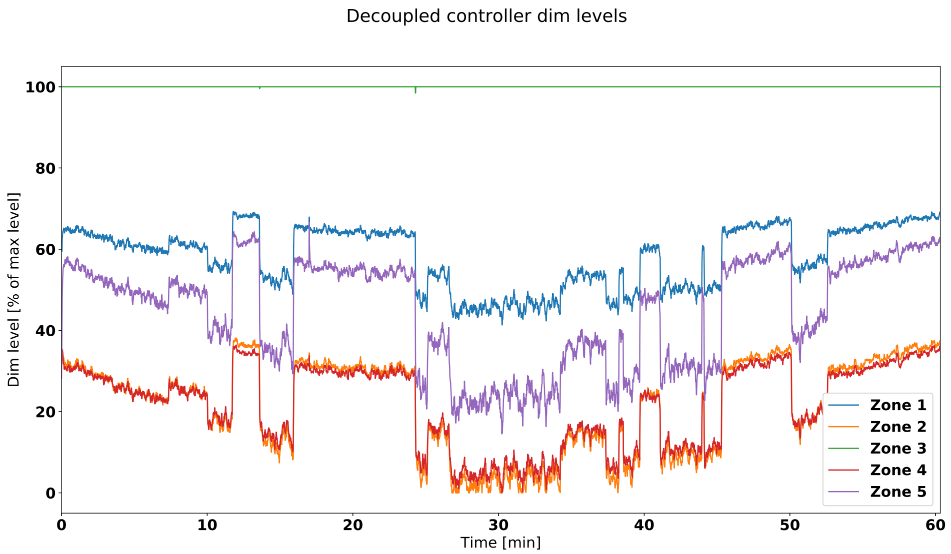

Figure 4.8: The dim level of each zone over the duration of the test of the decoupled controller

Figures 4.7 and 4.8 show the weakness of a decoupled controller. Sensor 3 was consistently under-illuminated, and the dim level of the controller for sensor 3 was at max. This might be solved by increasing the dim levels of neighbouring zones, but as the controller is decoupled this was not possible.

4.3.2 LQR on sensor illuminance

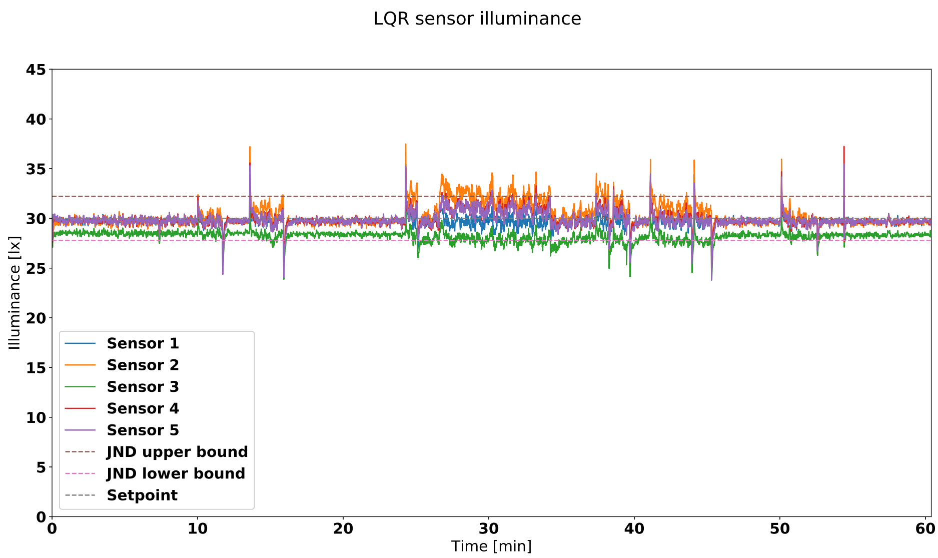

Figure 4.9: The sensor illuminance readings over the duration of the test of the LQR controller

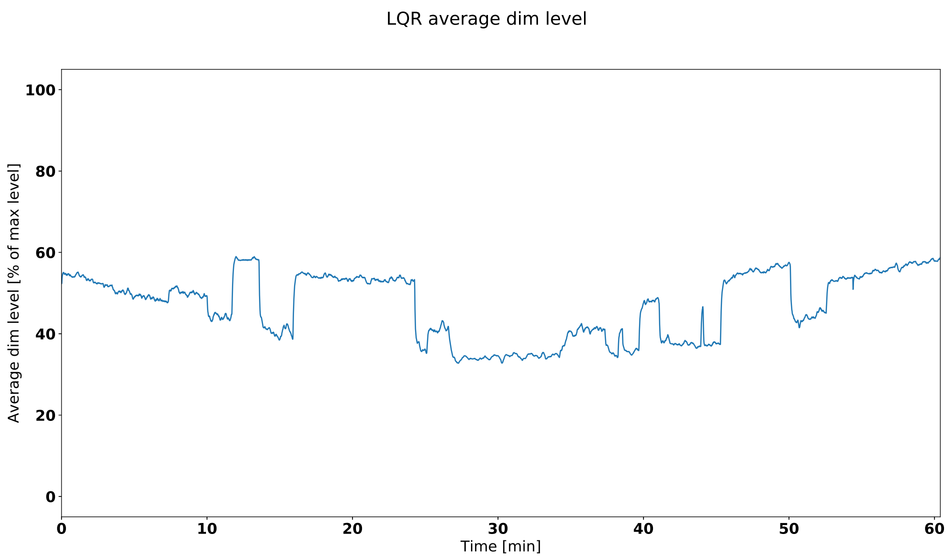

Figure 4.10: The average dim level of all lamps over the duration of the test of the LQR controller

As can be seen in figures 4.9 and 4.10 the LQR worked quite well for this application, as opposed to the decoupled controller the LQR minimised the mean squared error between the sensor readings and the setpoint, it also had individual control of each LED. The controller could therefore bring sensor 3 closer to the setpoint, and when it was impossible for the controller to bring all sensors close to the setpoint, the error is instead spread out so that no sensor was too over- or under-illuminated.

4.3.3 LQI total dim level controller

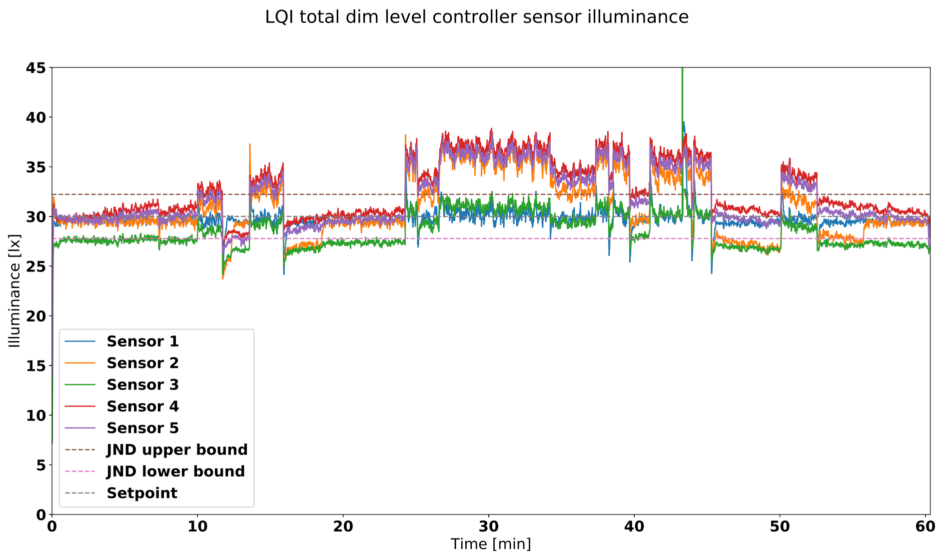

Figure 4.11: The sensor illuminance readings over the duration of the test of the LQI total dim level controller

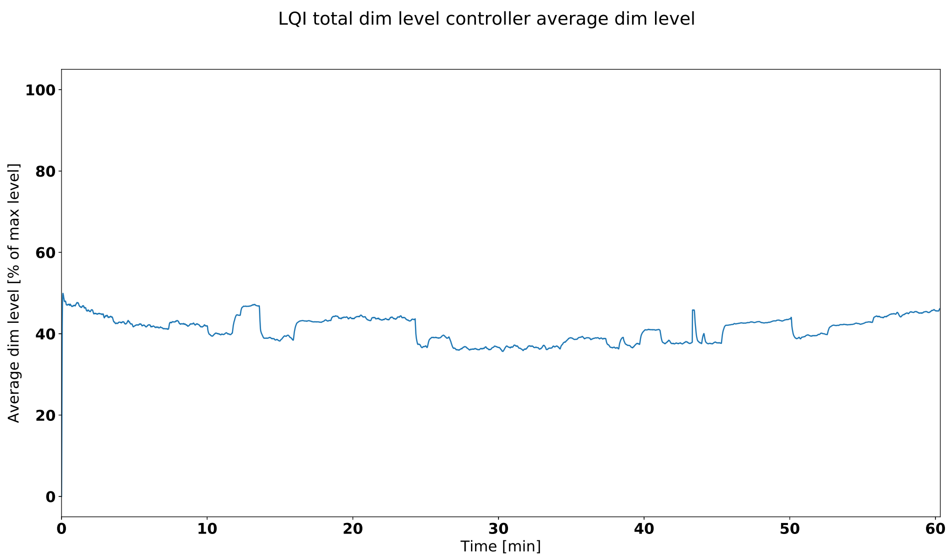

Figure 4.12: The average dim level of all lamps over the duration of the test of the LQI total dim level controller

As can be seen in figures 4.11 and 4.12 there was some over- and undershoot of the setpoint. The performance was decent but not as good as some of the other controllers.

4.3.4 LQI rate of change controller

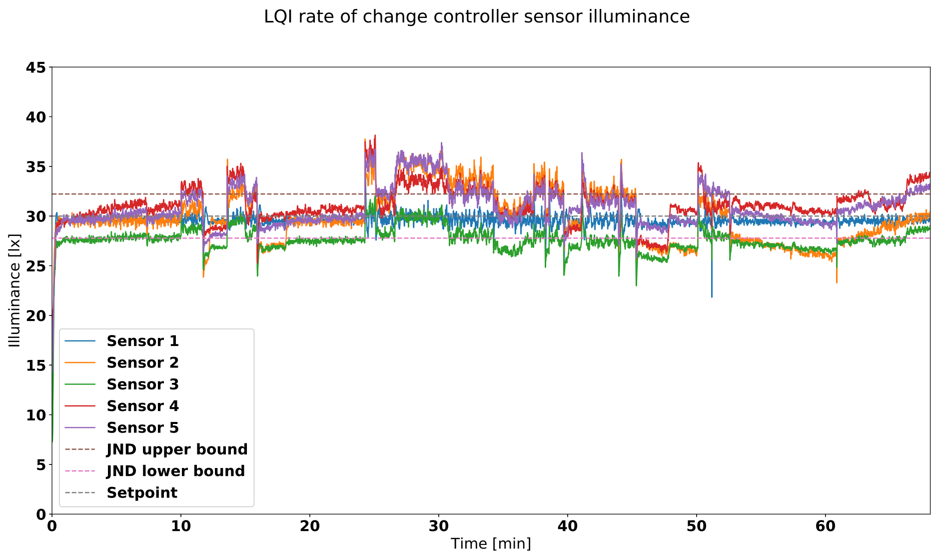

Figure 4.13: The sensor illuminance readings over the duration of the test of the LQI rate of change controller

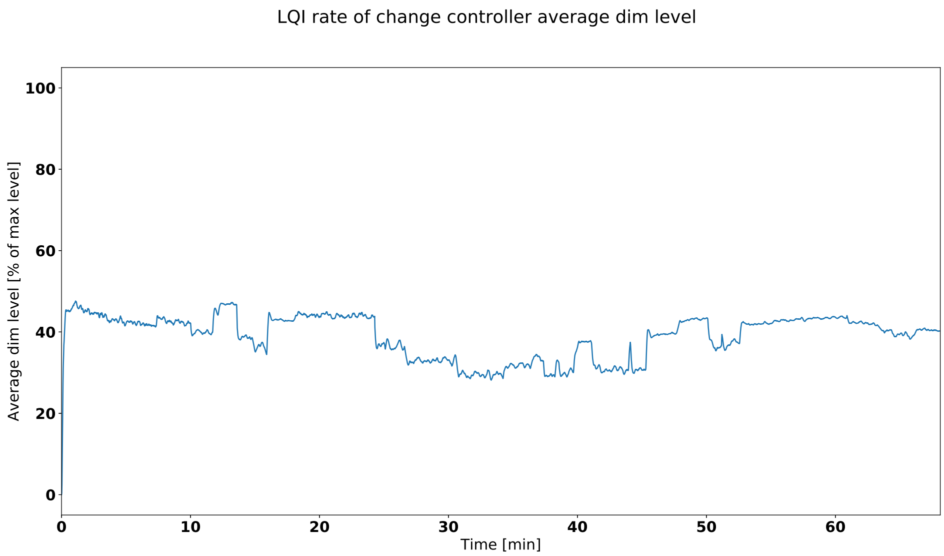

Figure 4.14: The average dim level of all lamps over the duration of the test of the LQI rate of change controller

Figures 4.13 and 4.14 show that the LQI rate of change controller performed decently, but not nearly as well as some other controllers.

4.3.5 Hand-tuned regulator

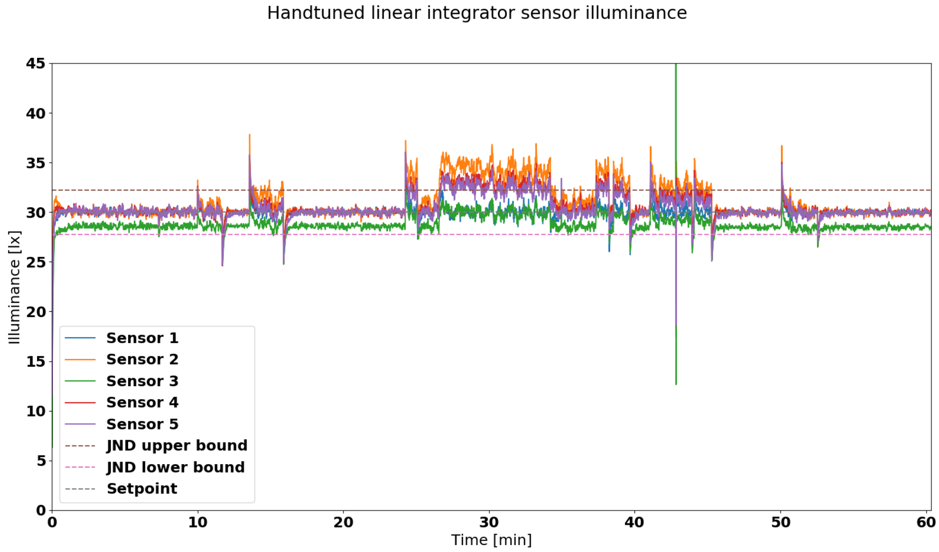

Figure 4.15: The sensor illuminance readings over the duration of the test of the hand-tuned regulator

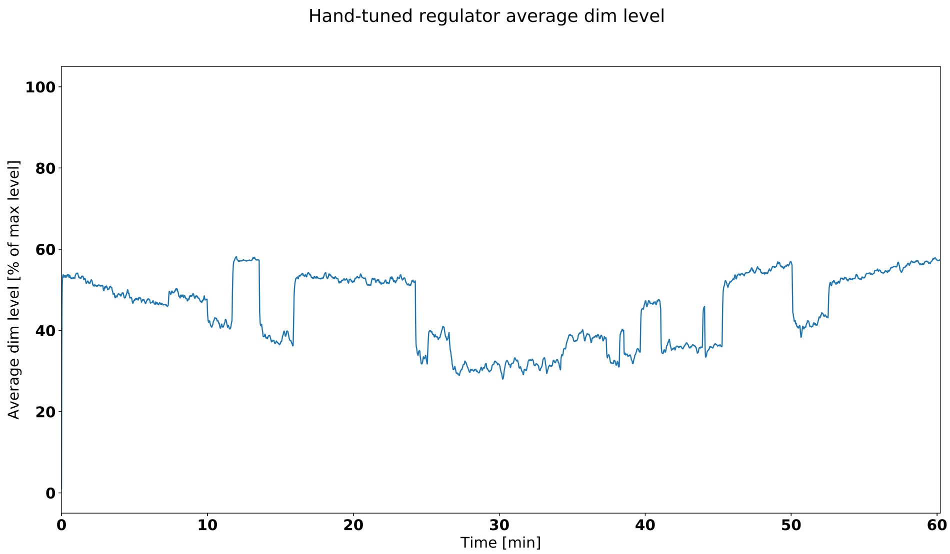

Figure 4.16: The average dim level of all lamps over the duration of the test of the hand-tuned regulator

The hand tuned regulator performed quite well, as can be seen in figures 4.15 and 4.16. There was no major overshoot except when the external light was high and the controller usually kept the illuminance within the just noticeable difference from the setpoint. In general the performance was good.

4.3.6 LP-controller on sensor illuminance

For the LP-controller it was found that setting the dim rate adaptively depending on the distances to the setpoint worked well. This helps the controller to not make large changes in the dim levels when it is close to the setpoint. It was therefore set according to $d = 100 + 9.9875 \sum_{i=1}^{n} |(s - y_i)|$, where n is the number of sensors. This means that the dim rate is 100 when there is no error, and 4095 when the average error is 100 lx. The highest allowable difference in dim level between neighbouring lamps was set to $\delta = 1025$, as this meant that lamps only are constrained by the dim level of lamps within three connections, since the maximum dim level is 4095 and seemed to work well.

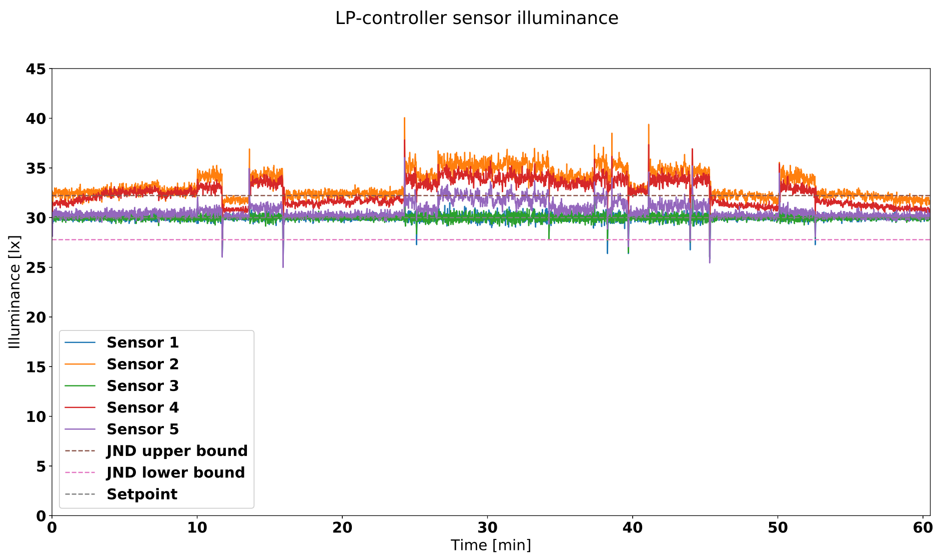

Figure 4.17: The sensor illuminance readings over the duration of the test of the LP controller

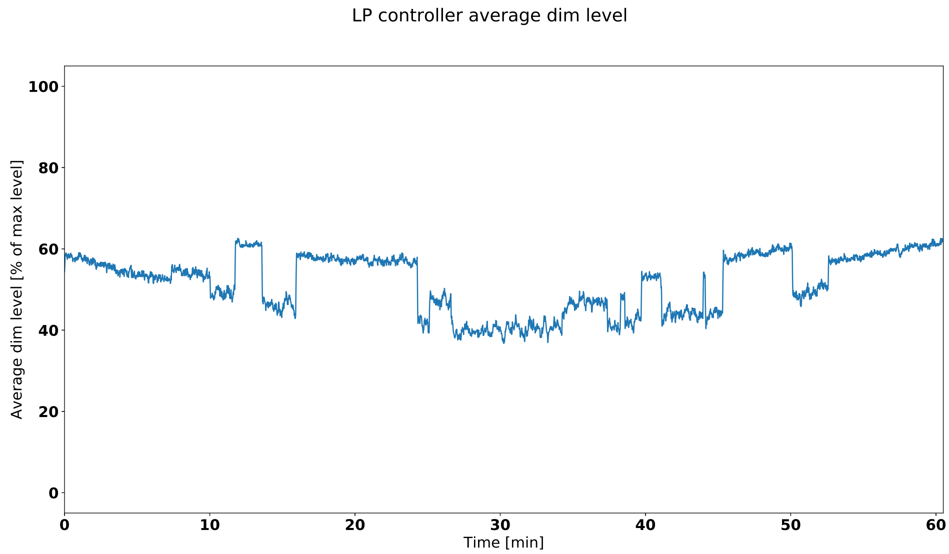

Figure 4.18: The average dim level of all lamps over the duration of the test of the LP controller

As can be seen in figures 4.17 and 4.18 the LP-controller also performed quite well. It also shows that, in contrast to the other linear controllers, the LP-controller guaranteed that all sensor illuminances, when possible, at least reached the setpoint. This comes at the cost of this controller generally having a higher average dim level, but is useful if one wishes for the setpoint to be a guaranteed minimum illuminance level.

4.3.7 Simulation of CLQR and MPC

An LQR with a slightly more aggressive control than used on the real system was simulated with the noise profile described in 3.11. This simulation was used to gain a benchmark to compare the CLQR and MPC controllers with. The tuning variables used for the controllers was the same for all three simulations. This was to make sure that the only difference was the controller architecture. The simulation results are shown in figures 4.19 and 4.20.

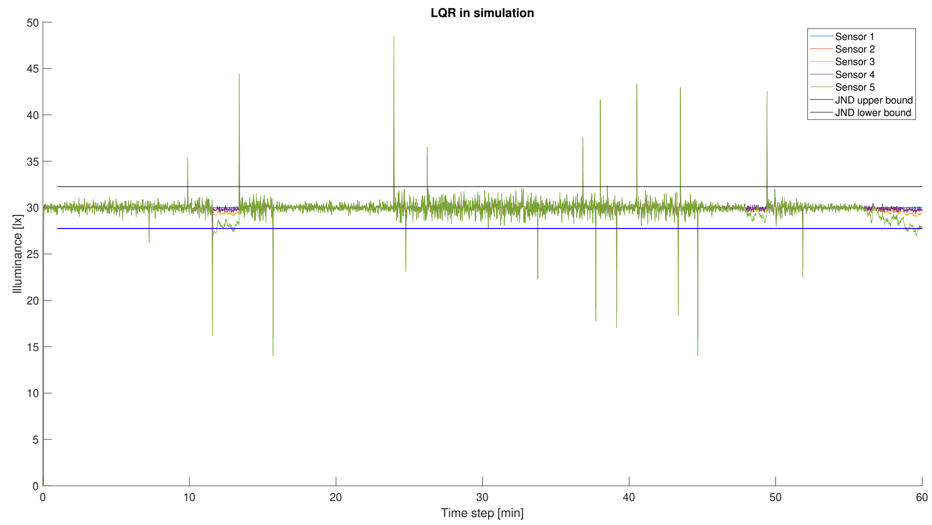

Figure 4.19: The simulated sensor illuminance readings over the duration of the LQR test

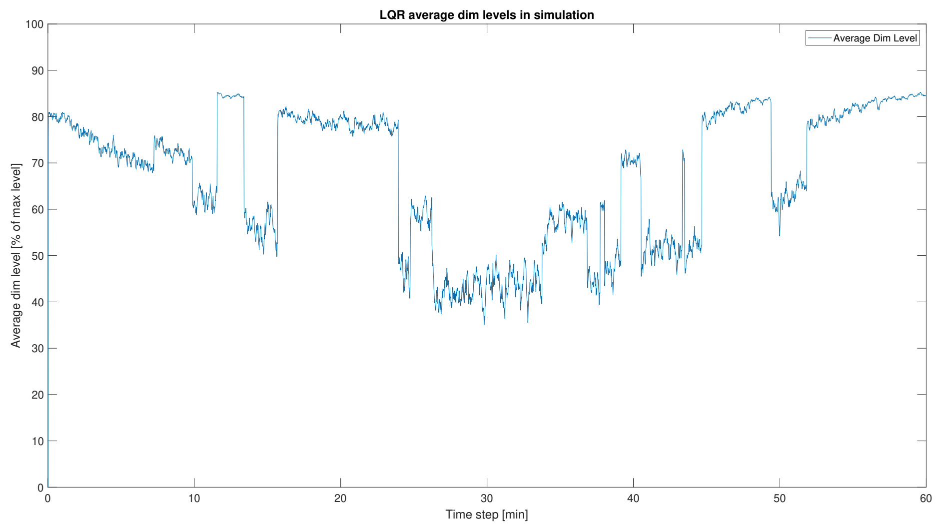

Figure 4.20: The average simulated dim level of all lamps over the duration of the simulation of the LQR controller

The Constrained LQR (CLQR), which made sure that the control policies was always within the acceptable dim levels $0 - 4095$, was then simulated in Matlab.

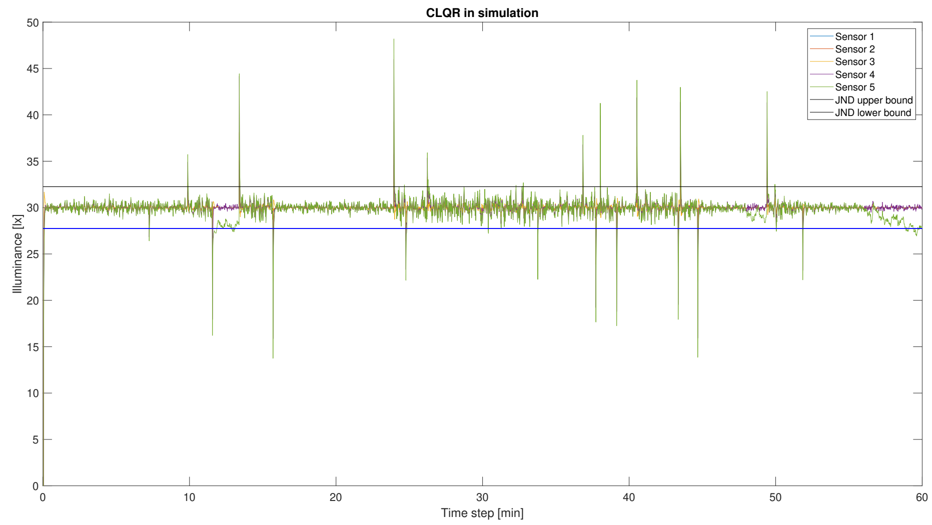

Figure 4.21: The simulated sensor illuminance readings over the duration of the CLQR test

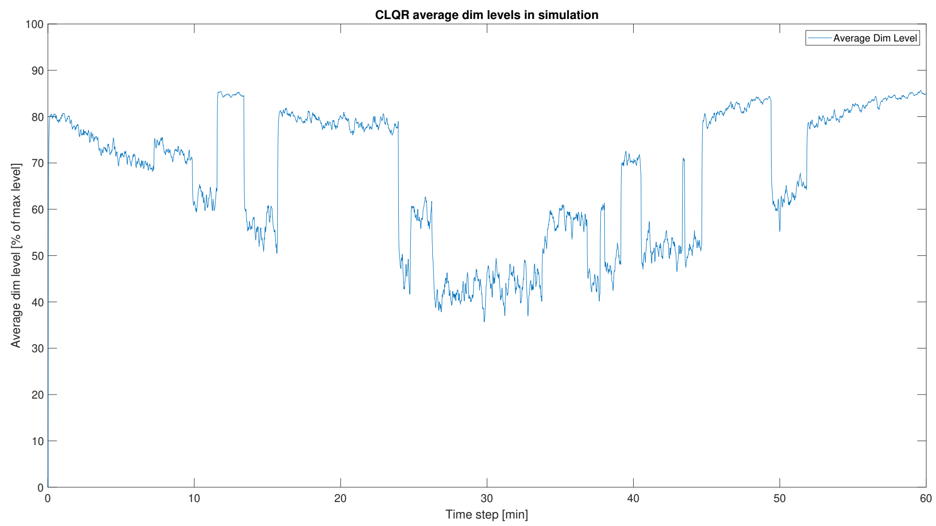

Figure 4.22: The average simulated dim level of all lamps over the duration of the simulated test of the CLQR controller

The MPC was then simulated in Matlab with a control horizon of 10 and the same constraint on the outputs as the CLQR.

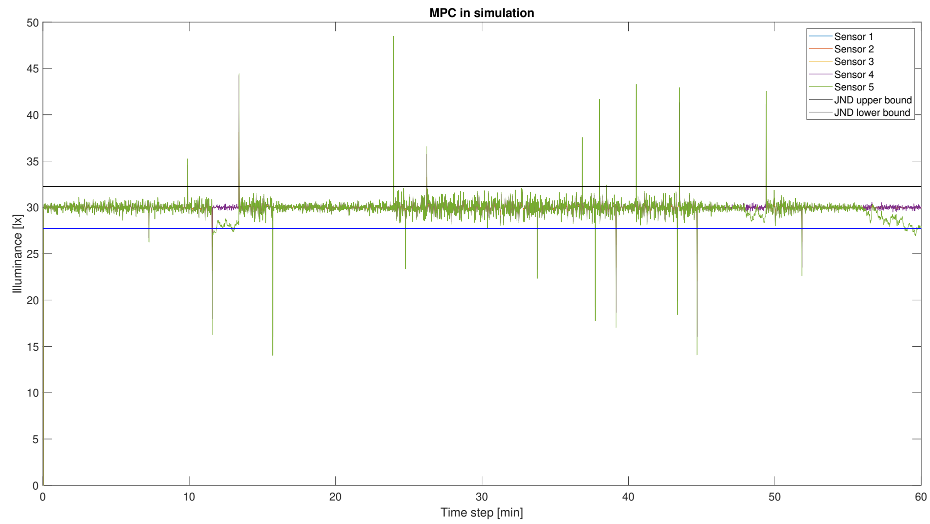

Figure 4.23: The simulated sensor illuminance readings over the duration of the MPC test

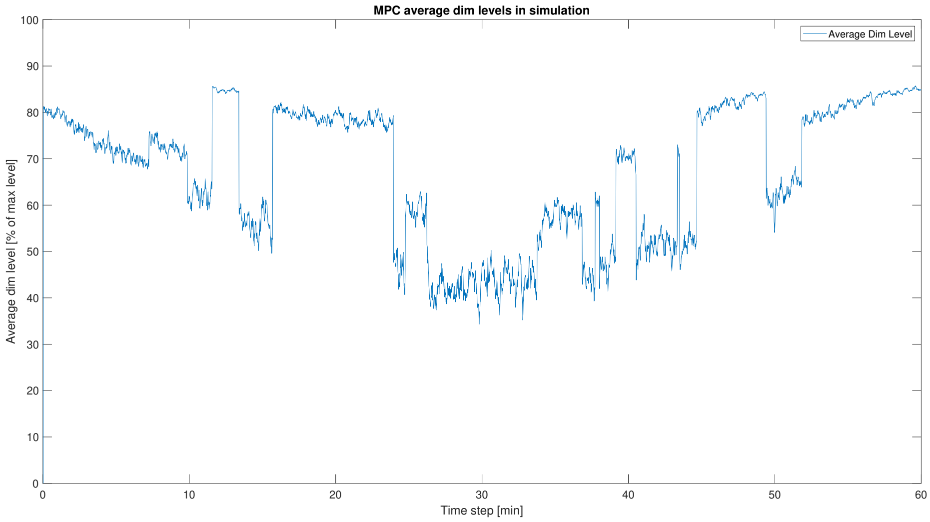

Figure 4.24: The average simulated dim level of all lamps over the duration of the simulated test of the MPC controller

As can be seen, in figures 4.22, 4.23 and 4.24, they had a very similar performance.

4.4 Performance tests: MIMO controllers, controlling illuminance at ground level

For the architectures of the controllers tested in this section see section 3.6. The same daylight profile was used to test these controllers as in the previous section, but scaled up so that the illuminances were larger as the ratio between how much the MIMO system could illuminate the ground as compared to the sensors was higher than the same ratio for the daylight disturbance. These tests were done over three days in 8 hour periods for a total of 24 hours of testing, the test was run an hour each for each zone.

4.4.1 LQR control of ground illuminance

This LQR used the same tuning as the one used for controlling illuminance at the sensors, as it was found to work well.

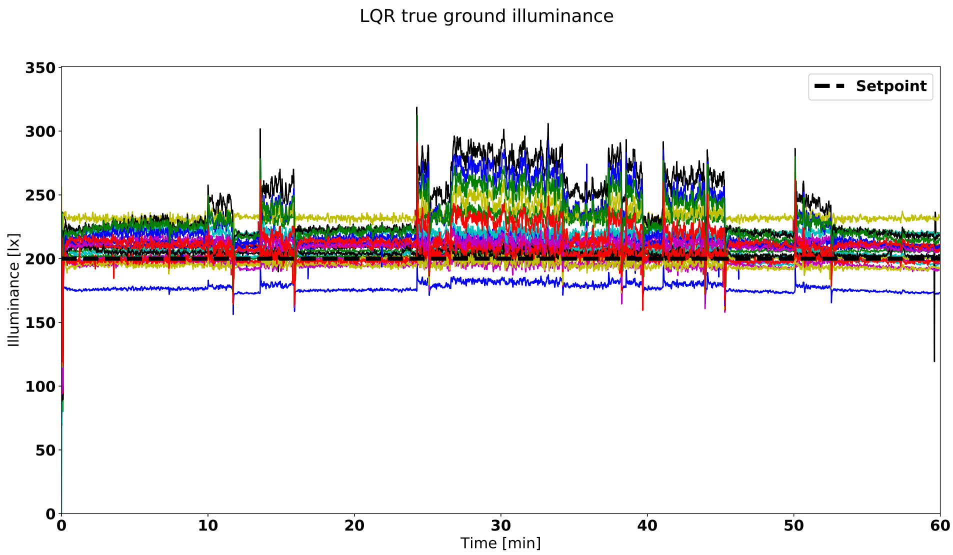

Figure 4.25: The true ground illuminances in the 24 zones, note that these measurements where taken in 24 separate tests and not at the same time

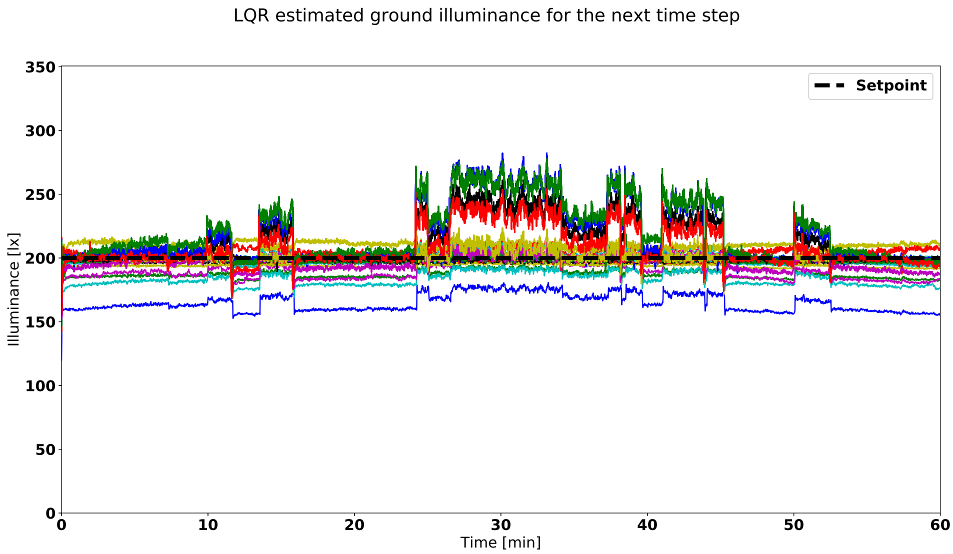

Figure 4.26: The controllers estimate of the ground illuminance for the next time step, i.e after the new dim level has been set and before a new measurement is taken.

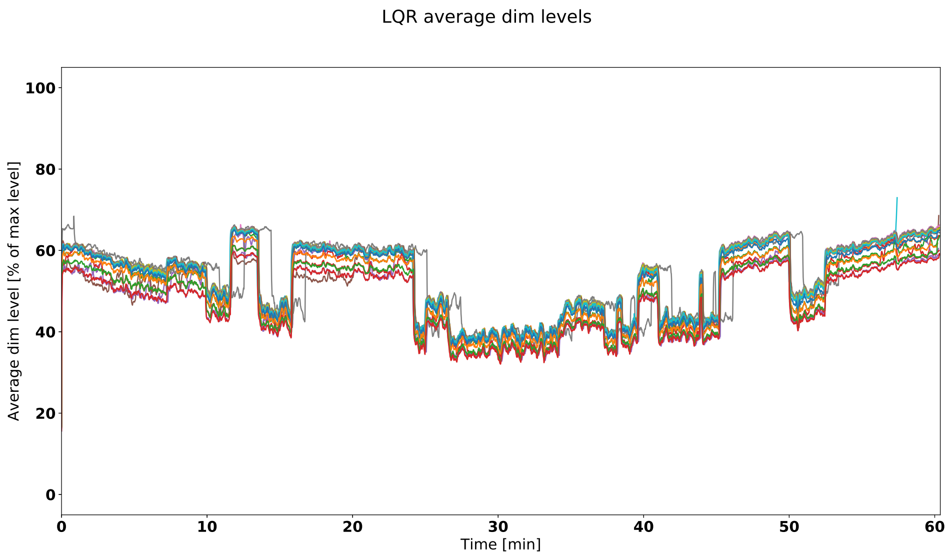

Figure 4.27: The average dim level for each test

As can be seen in figures 4.25 and 4.26, the LQR seems to control the ground illuminances fairly well. It managed to keep most zones within the just noticeable difference of the setpoint except when some zones were over-illuminated by daylight. See appendix A.1 for individual plots of estimation and true illuminance for each zone. Figure 4.27 shows that the dim levels varied slightly in the 24 tests. This was most likely a result of changing ambient illuminance in the office where the tests were conducted. The effect was not very large, as the ambient illuminance in the office did not affect the illuminance in the MIMO system very much by design.The performance was relatively good and the projection appears to work fairly well.

4.4.2 LP-controller of ground illuminance

For the LP-controller of ground level illuminance it was found that the dim-rate constraint was unnecessary, the dim rate was therefore set to $d = 4095$ meaning that all lamps always can change their dim level within $0 - 4095$. This was a result of the fact that the lamp inside each zone had by far the biggest effect on the illuminance of the zone, meaning that the controller only changed the dim level of a lamp by a large amount when the illuminance in its zone changed rapidly. With that in mind, and that the constraint that neighbouring lamps need similar dim levels was removed, this controller had no tuning parameters, it simply went to the dim setup that minimised overshoot and dim levels while reaching the setpoint in all zones each time step.

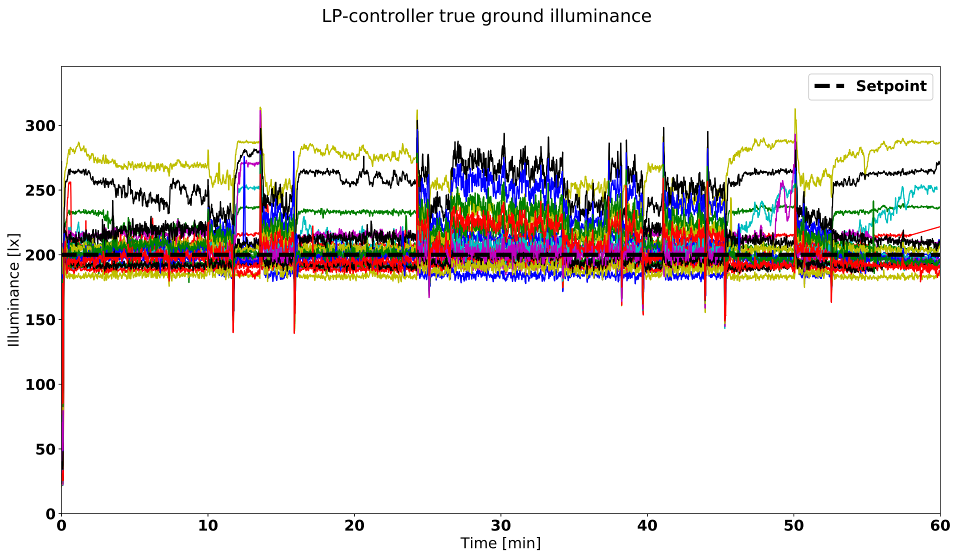

Figure 4.28: The true ground illuminances in the 24 zones, note that these measurements where taken in 24 separate tests and not at the same time

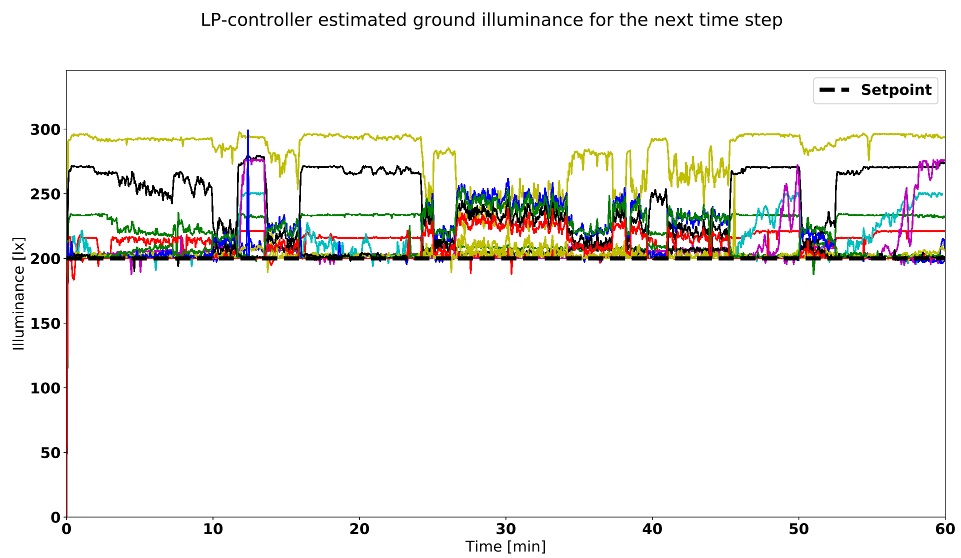

Figure 4.29: The controllers estimate of the ground illuminance for the next time step, i.e after the new optimal dim level has been set and before a new measurement is taken.

Figure 4.30: The average dim level for each test

Figures 4.28 and 4.29 show that the LP-controller performed quite well. Some zones were however forced to be quite over-illuminated as a result of the corner zones of the MIMO system not having as many nearby lamps to illuminate it, leading to those zones generally being darker. For a clearer picture of the performance, see appendix A.2 where plots of each individual zone can be seen. Figure 4.30 shows that the dim levels were slightly different in the 24 tests, this is a result of the ambient light in the office where the tests were performed changing throughout the days, as the tests were done over a three day period. The change is however not very large, as the ambient light of the office did not illuminate the inside of the MIMO system very much by design.

4.5 Evaluation of energy savings

Tests for potential energy savings were performed on all controllers of ground/-workspace illuminance. The results are presented in this section.

4.5.1 SISO controller

The chosen day for the evaluation of the SISO controller energy savings was a partly cloudy day at the end of April. How the relative energy savings were found is described in section 3.3.2.

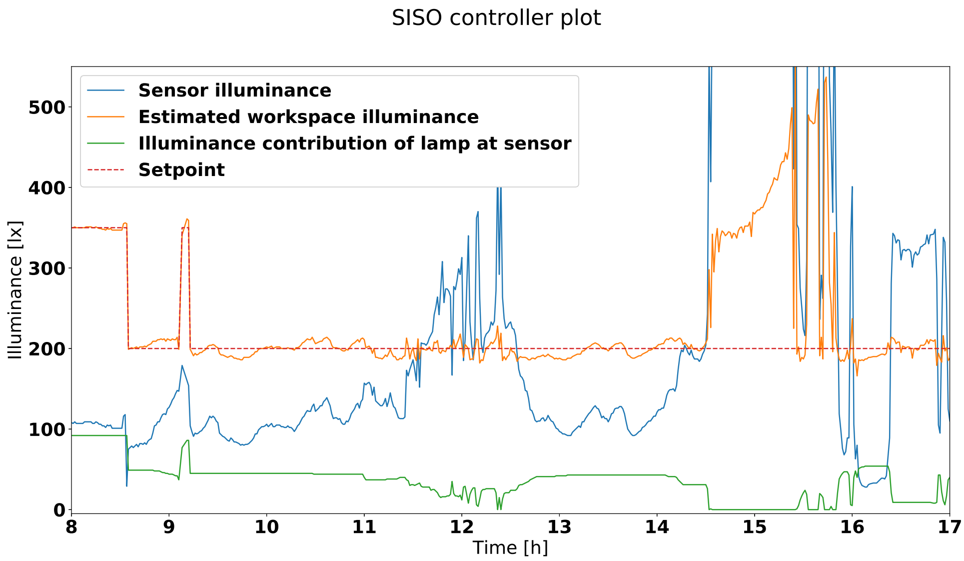

Figure 4.31: The data logged from the SISO controller for the chosen day between 08:00 and 17:00.

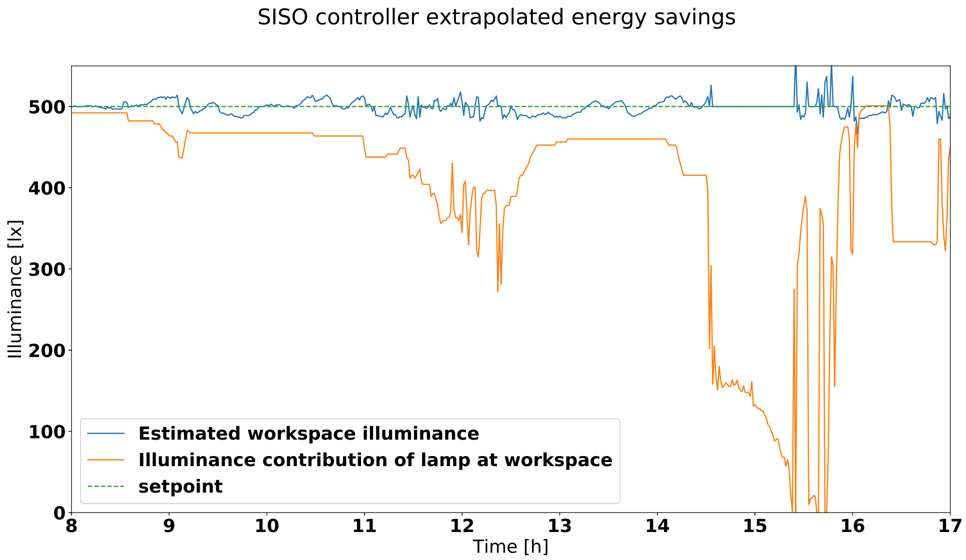

Figure 4.32: The extrapolated controller contribution at the workspace if the setpoint had been 500 lx troughout the entire same day as figure 4.31

From the extrapolated behaviour of the controller, had the setpoint been at 500 lx, the average illuminance contribution from the controller at the workspace would have been 399 lx. This means that, in comparison to an uncontrolled lighting system that always gives 500 lx contribution at the workspace, the relative energy savings for this particular day would have been 20%.

A simulation of the SISO controller, assuming perfect tuning, on the daylight profile used for the energy test of the MIMO controllers, described in 3.7.2, was also done. The results looks like:

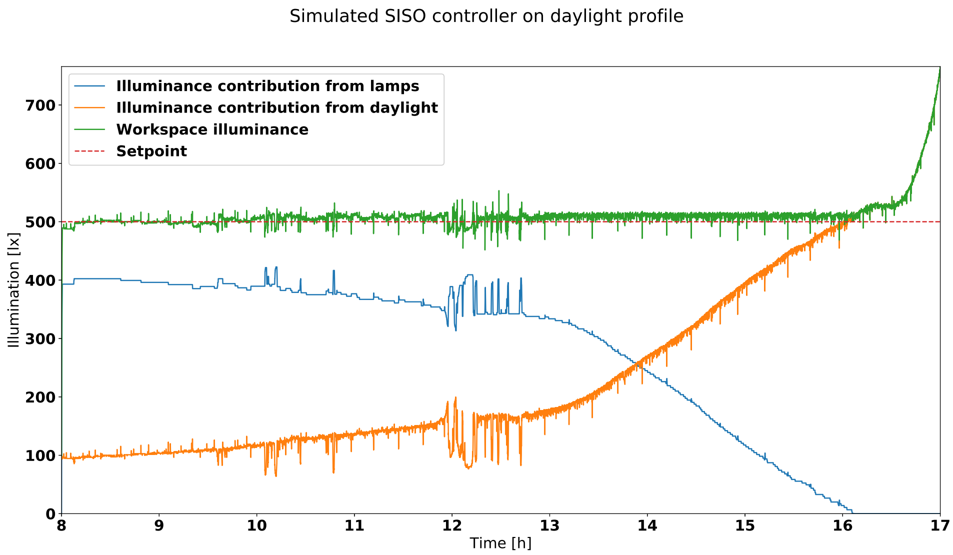

Figure 4.33: A simulation of the SISO controller on the daylight profile used for the energy test of the MIMO controllers.

In comparison to an uncontrolled lighting system that always gives $500lx$ illuminance contribution at the workspace the relative energy savings were 46%. When compared to a system where the lamps are turned off when enough daylight illuminance is present on the workspace the relative energy savings drop to 39%.

4.5.2 MIMO controllers

The procedure of how the energy savings of the MIMO controllers were evaluated is described in section 3.7.2. The measured daylight profile from the workspace of the office, scaled by $\frac{2}{5}$ looks like:

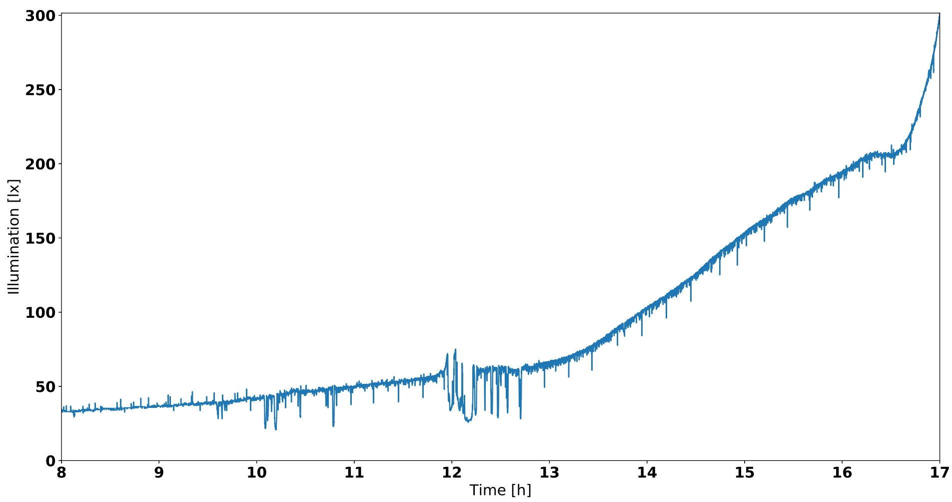

Figure 4.34: The daylight profile used for testing energy savings of the MIMO controllers of ground level illuminance.

4.5.2.1 LQR controller energy savings test

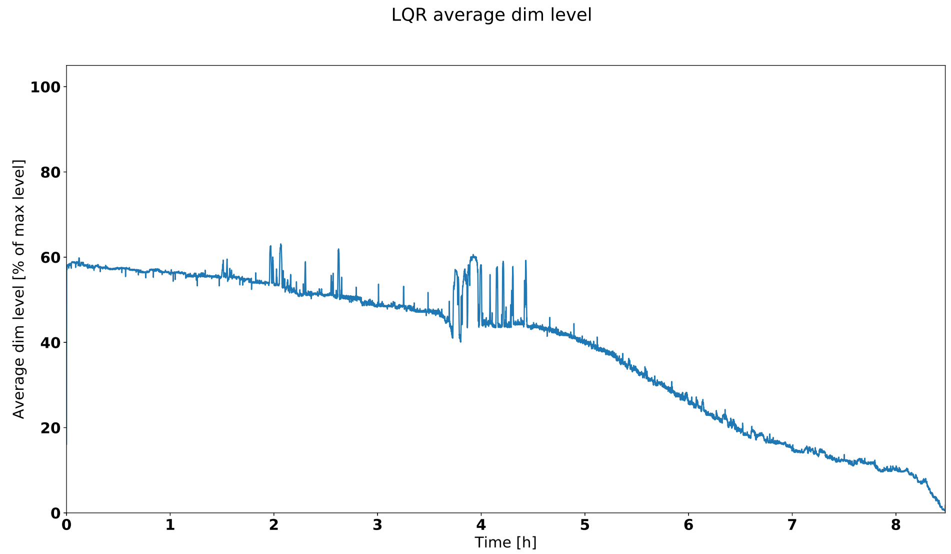

Figure 4.35: The average dim level of the lamps during the LQR energy savings test

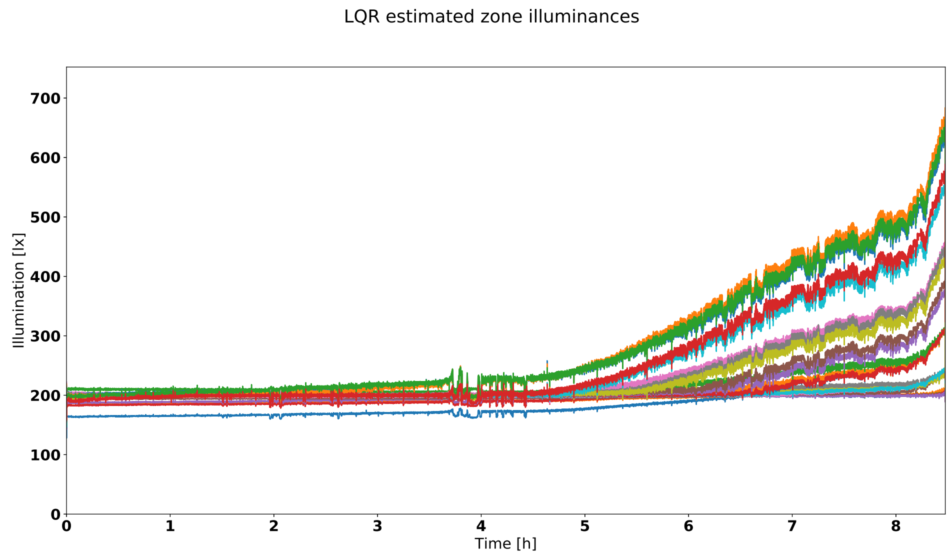

Figure 4.36: The estimated ground zone illuminances for the LQR energy savings test

As can be seen in figures 4.35 the average dim level of the lamps were lower than d^* throughout the entire test. This was expected as there were some daylight even at the beginning of the test, being about 08:00 in the morning. This meant that the controller without a doubt saves energy in comparison to an uncontrolled MIMO system. However, as shown in figure 4.38, with the daylight profile many zones were very over-illuminated, as a result of excessive daylight. In a real life scenario blinds might be used in a situation like this one, which would lead to lower energy savings with the lighting system. Using equation 3.15 the relative energy savings this controller achieved throughout the test was 49%.

4.5.2.2 LP controller energy savings test

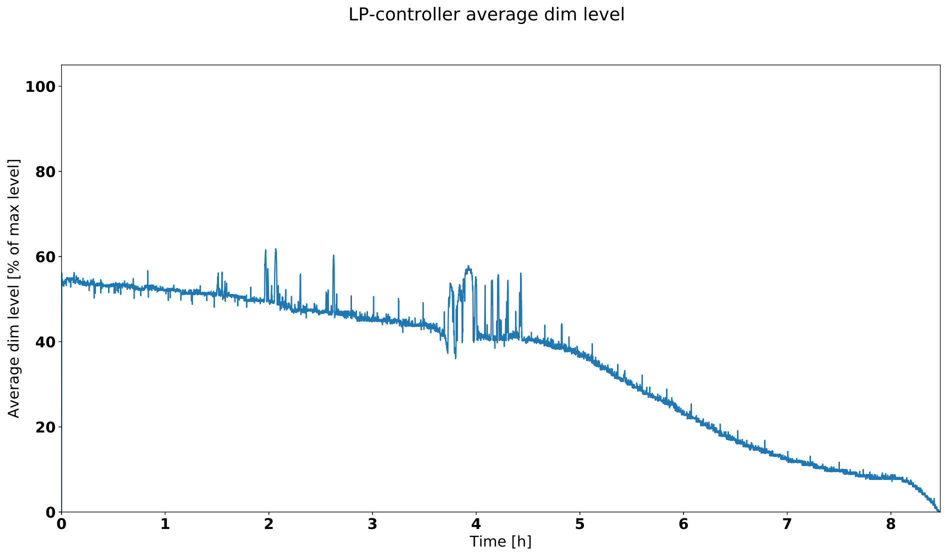

Figure 4.37: The average dim level of the lamps during the LP-controller energy savings test

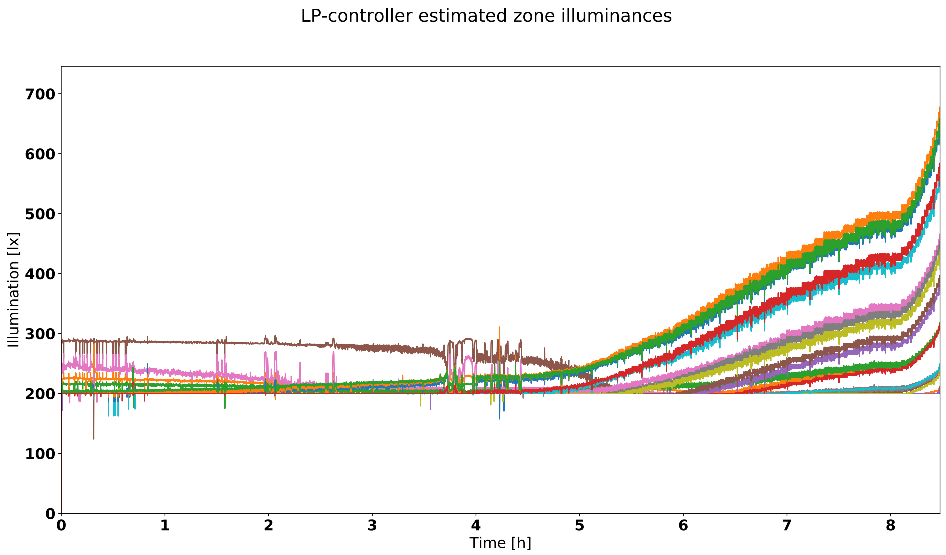

Figure 4.38: The estimated ground zone illuminances for the LP-controller energy savings test

The behaviour of the LP-controller during this energy test appeared to be quite similar to the LQR, except for that the estimated zone illuminances were all at or above the setpoint at all times, except for a few spikes throughout the test. There was one zone that was very over-illuminated in comparison to the results of the LQR, that is zone 6 (brown in the plots), this was due to the LP-controller using the lamp in this zone to bring zone 1 (blue in the plots) to the setpoint, which otherwise would be slightly under-illuminated. This can be seen in the results for the LQR, where zone 1 was under-illuminated. Using equation 3.16 the relative energy savings this controller achieved throughout the test was 53%.

5
Discussion

5.1 SISO controller on workspace illuminance

The chosen SISO controller worked well and achieved a desired illuminance level. The occupants of the room described that they did not notice changes made by the controller except for when the lamps turned on/off. This controller in general worked well when well tuned and the method seems like a viable control method. There was in general a fairly small error in estimation of the workspace illuminance which varied over time, however, this error was for most of the time small enough to be acceptable, it was not noticed by the occupants.

5.2 MIMO controllers on sensor illuminance

This section presents a discussion on the performance of the MIMO controllers for sensor illuminance.

5.2.1 Decoupled controller

Figure 4.7 shows that the decoupled controller performed decently. The problem in this application is that sensor 3 was constantly under-illuminated. This was a direct result of that all lamps in the zone of sensor 3 was also in one or two of the other zones which meant that the controller for zone 3 did not have full control of any lamp. The third zone might have performed better if the four closest lamps were excluded from the other four zones, as this would have given the controller for zone 3 more control. This might however also lead to the other sensors becoming slightly over-illuminated instead, as it seems from all other controllers that for most of the time it is not possible to settle perfectly on the setpoints at all five sensors at the same time. The strength of this controller is the simplicity of implementing it, as a SISO controller for light control compared to a MIMO controller is fairly simple to construct and get a decent performance on with no other calibration.

5.2.2 LQR

The linear quadratic regulator performed well and reached a region around the setpoint for all sensors in figure 4.9. In comparison to the decoupled controller sensor 3 reached a value close to the setpoint. The controller then reacted in an acceptable way for the entirety of the test with some over- and under-shoot which was quickly compensated back close to the setpoint. One major downside with the linear regulators is that it places the illuminance levels around the setpoint and not on or over as the LP controller does. This is due to the fact that the LQR minimises the mean square error which makes no major difference in normal use, but might become problematic if there is a strict requirement on the illuminance level. Furthermore, a major advantage of the LQR is that it is computationally cheap, as the control signal is calculated from one matrix multiplication each time step. However, a disadvantage is that the controller-gain matrix has to be calculated before control is possible, but this only has to be done once.

5.2.3 LQI

Both the LQI controllers performed worse than the other controllers. They were around the setpoint but not as close as the LP-controller, hand tuned regulator and LQR. This was probably due to the addition of the integral states that in the rate of change controller is not necessary. In the case of the total dim level controller, while necessary, it is slower to react than the LQR and can have problems with integral windup. These controllers also have a higher computational cost than the LQR and hand-tuned regulator, as it has double the amount of states. Since the performance is worse while adding more tuning variables it is unnecessary to add the extra integral states to the rate of change regulator. Especially since the LQR has $\mathbf{A} = \mathbf{I}$, the model therefore contains an internal integral, rendering external integration unnecessary for achieving good performance.

5.2.4 Hand tuned regulator

The results in figure 4.15 show that the hand tuned regulator performed almost on par with the LQR. The advantage with this controller is that, since all elements of the gain matrix are positive, if the setpoint is reachable within the constrained dim levels, the regulator will always be able to reach it, even with the enforcement of the constrained dim levels. This is something that can happen with the quadratic regulators, as there are negative elements in the gain matrix, meaning that some dim levels will be driven down when some sensors are under-illuminated. This controller also has the advantage that it is simple to implement, only the **B**-matrix is necessary, the only tuning parameter is the constant to multiply with **B**, which changes the aggressiveness of the controller.

5.2.5 LP-controller

The LP-controller performed very well. This is not surprising as it is the solution to a custom tailored optimisation problem. The spread in illuminance between the sensors was similar to the LQR, furthermore, this controller has the advantage that it guarantees that the setpoint is at least reached on all sensors. This is beneficial if there are regulations in place which require some minimum illuminance level. A major disadvantage of this controller is the large computational complexity, and that the time to solve the optimisation problem with the simplex algorithm varies largely. For the sensor illuminance control the solving is fast enough to use a control frequency of 1 Hz. However, the controller in itself is completely independent of sampling time, so any frequency could be used so long as the optimisation problem can be solved in that time. In fact, the implementation used here had no hard sampling time, a new measurement was simply taken as soon as the lamps had reached the new optimal dim levels.

5.2.6 Evaluation of MPC and Constrained LQR control in simulation

As can be seen in section 4.3.7 the LQR in simulation had a similar performance as the real system, but not exactly the same. This was a result of the daylight profile not being applied on the sensors exactly the same as in the real system. In the simulations the changes in daylight happened at exactly the same time as the controller update, which was not the case in the real tests. In simulation the **B** matrix was also assumed to be exact, which was also not the case in reality. This caused the performance in simulation to be better than in reality.

The results show that the constrained LQR and the unconstrained LQR have a very similar performance. This is due to the final tuning of the unconstrained LQR being chosen with the constrained range of the dim levels in mind.

The MPC had a similar problem as the CLQR but amplified. The constraint on dim levels was enforced, in this case over 10 time steps but the controller could reach an ideal position in one step. Meaning that the rest of the calculations was mostly wasted. The result was extremely similar, both in average dim level and sensor illuminance to the regular LQR. This occured due to the lack of known long term noise in the system.

5.2.6.1 The problem with using MPC

Model Predictive Controllers are not ideal for use in the case of daylight harvesting. This is due to several factors. First of all, the model predictive controller needs information or approximations of future errors to be able to do a good prediction. This is not available in a practical application. Secondly, if future information about the disturbance was available then it is extremely hard to run it on a microcontroller due to the computational complexity and memory requirements of the algorithm. It would not be possible with the desired sampling time for this thesis. If the data was available to do N prediction steps into the future on the MIMO system tested in this thesis the constraint matrices would be of the size $[29N \times 48N]$, if the only constraint was on the control signal for the entire horizon. The control horizon will most likely need to be equal to the prediction horizon since the controller would need to guarantee that the control signal is within the constraints.

Ideally if good data on future daylight was available and computational limits was ignored, a horizon of about one minute might yield a good result, a longer horizon would probably yield an even better performance. But is not possible with the current hardware. This might be computationally feasible if the control frequency were to be severely reduced, to maybe $\frac{1}{60}$ or $\frac{1}{30}$ Hz, which would mean a horizon of 1 or 2 time steps respectively to have a span of of one minute. While a shorter horizon would yield a small gain in performance if any, as daylight tends to change very slowly. It would not be able to compensate for the semi-fast changes of say, the sun moving behind a cloud or similar. A CLQR on the other hand is much more feasible when it comes to calculation and memory requirements and does not require information of future noise. The CLQR would guarantee that the solution is within the constraints on the dim levels, if such a solution exist. Which was a potential problem with the unconstrained controllers. But in the end the behaviour is similar to what is achieved with a well tuned unconstrained LQR as long as the setpoint is reachable, which is much cheaper to calculate.

5.2.7 Discussion of the MIMO Controllers, controlling sensor illuminance

There were two controllers that performed the best when controlling illuminance at the sensors. These were the LQR and the LP controller. Both of these have a good performance when it comes to disturbance rejection and bringing the illuminance close to the setpoint. These controllers have different advantages. The LQR needs to be tuned but is very fast and computationally cheaper. The LP-controller on the other hand does not need to be tuned offline and can be implemented more or less directly. But it has a higher calculation cost and has a calculation time that is changing depending on the state of the system.

5.2.7.1 Performance of the models in controllers

It was found through simulation and testing that for a controller to have a decent performance it needs to have some kind of integral, either an internal or an external. This means that the model with $\mathbf{A} = \mathbf{0}$ requires either a I-regulator in a SISO system or a LQI in a MIMO system to have a good performance. While the model: $\mathbf{A} = \mathbf{I}$ has an internal integrator in the plant and therefore does not need an external integral. This means that a controller based on this model reduces the amount of tuning variables and computational complexity online since a LQI has double the amount of states. It also means that no extra anti-windup function is needed. Due to these advantages and results from 4.3 it can be concluded that the model described in 2.6 is the superior model in respect to regulator design since LQR:s based on that model performed the best.

5.3 MIMO controllers on ground illuminance

This section presents a discussion on the performance of the MIMO controllers for ground illuminance.

5.3.1 LQR

The LQR performed well, as shown in figure 4.25, all but one of the the zones was close to the setpoint throughout most of the test. Comparing figure 4.25 with figure 4.26 it can be seen that the estimation of the ground illuminances was close to the real value over time in almost all ground zones. Looking at the average dim levels in figure 4.27 it can be seen that the dim profile was similar for all 24 tests with some difference depending on the ambient light in the office during the test. One of the dim plots appears to have a slight lag in it, this was most likely a result of the logging of the data starting a little later in comparison to the other tests.

5.3.2 LP-controller

The LP-controller for illuminance on ground level has the same advantages as the one for illuminance on the sensors. With the added uncertainty in estimation it is now however possible for some zones to be slightly under-illuminated, the only guarantee is that the controller will, if possible, control the estimation to be greater than or equal to the setpoint. As can be seen in figure 4.28 tough, the estimation of all zones was good enough for the ground zone illuminances to only fall below the just noticeable difference of the setpoint when there was a very fast change in the disturbance.

5.3.3 Conclusions from the MIMO controllers

From comparing the different controllers performance when controlling on the sensor it can be found that the LQR and the LP controllers performed best. Both of these performed well also when controlling on the ground. The LP-controller has the advantage of guaranteeing a minimum illuminance level in the estimation of every zone illuminance. The LQR, on the other hand, spreads the error out, above and below the setpoint between the different zones.

5.4 Potential energy savings

All the energy savings presented depends on one major factor, the amount of daylight entering the room and how this behaves. This means that depending on the daylight as well as the setpoint the controller will behave differently and different savings are possible. The results on energy savings for all controllers seem to fit well into the findings of previous works, where the long term energy savings of daylight harvesting systems typically are somewhere between 10-40%. Energy savings close to 50% specifically on a sunny day should therefore be feasible. As well as the energy savings of 20% found for the SISO controller on a semi-clear day.

5.4.1 SISO controller

The relative energy savings of the SISO controller for workspace illuminance achieved on the chosen day was extrapolated to be about 20% in comparison to an uncontrolled lighting system. The accuracy of this extrapolation should be quite high, as only the constant for transforming illuminance contribution at the sensor from the lamps to illuminance contribution at the workspace is needed, and this constant seems to be quite accurate, as the estimation of the workspace illuminance is very good when there is little to no daylight present. However, the controller would not be as aggressive in reality as it appears in the extrapolation, which leads to some loss in accuracy. Also, the control was extrapolated to be perfect when the lamps were turned off, which would not be the case in reality. However, as the estimated workspace illuminance is always centred around the setpoint over time this approximation should not cause a large change in accuracy of the relative energy savings that could be achieved.

Since the data for this test was retrieved from a partly cloudy day, it is fair to assume that on a day with good weather the energy savings would be larger. This was confirmed with the simulation of the SISO controller on the daylight profile used for the energy tests of the MIMO controllers. The simulation showed that, with a perfectly calibrated SISO controller, the energy savings would be 46%. This is probably close to what the SISO controller on the given day would achieve in reality, as the estimation of workspace illuminance was quite good in the performance test.

5.4.2 LQR

The LQR shows good results in the aspect of energy savings with a total energy saved of 49%. The estimated zone illuminances were in the beginning of the test, just like in the performance test, spread out around the setpoint. Later in the test when the daylight became too large the zone illuminances were instead placed on or above the setpoint due to the controller not being able to bring the illuminances down.

5.4.3 LP-controller

The LP-controller energy test gave 53% energy savings as compared to an uncontrolled system. This might seem a bit strange, as the zone illuminance were all higher than those for the LQR energy test. This was most likely due to slightly different ambient illuminance from the office during the energy tests, and shows that this test gave a slightly higher energy savings estimation than would have been achieved with the daylight profile in reality. A small part might also be that the LP-controller minimised the dim levels of all lamps in its objective function, however, the zone illumiances for the LP-controller energy test were larger, while the dim levels were lower, which probably is an indication that the reduced dim levels compared to the LQR is due to higher ambient office illuminance entering the MIMO system.

5.4.4 Energy Savings in comparison to the test

All energy saving tests on the MIMO systems were done with daylight from good weather in the late spring. This means that the energy savings over time would be lower, as the savings are lower during cloudy days, and during late autumn, winter and early spring due to less sun hours.

5.4.5 Accuracy of energy savings test of MIMO system

It is hard to draw any absolute conclusions on how accurate the energy savings retrieved from the energy savings test of the MIMO controllers actually were. There are many factors which differ from how real daylight disturbance behaves. The lamp which acts as a daylight disturbance had a control frequency of $1\,Hz$, while daylight changes in a approximately white Gaussian manner, this should however not have affected the energy savings results, as the changes in daylight second to second is very small in any real life scenario. Another factor is that the daylight in the test came from one light source, which is not the case for true daylight. Daylight is a combination of direct sunlight, which is completely directionally homogeneous, and reflected sunlight from objects and clouds outside the room, which is diffuse. The effects of this on the accuracy of the energy savings tests is hard to determine. However, there are also many other factors which would affect the energy savings of the MIMO controllers, such as the amount, and size of windows. There was also ambient light in the office where the test was conducted which affected the tests, this will give a higher estimation of the energy savings than would have been achieved if the MIMO controllers were tested purely on the daylight profile. The actual energy savings would probably, without the ambient office light affecting the system, be closer to that of the SISO controller at 46% energy savings.

The MIMO system used here would most accurately be compared to a large unfurnished open room with a window wall, which is an ideal scenario. If used in a furnished office with a row of windows on one wall the energy savings, under the same daylight conditions, would be smaller than those retrieved in this thesis. However, the test was done with a daylight profile retrieved from an office with westward facing windows, if the windows were facing towards the south the savings might be larger as direct sunlight would be available throughout most of the workday. Respectively if the windows would be north facing then the energy savings would be smaller.

The advantage of running the energy saving test on a simulated daylight profile instead of real daylight is that both evaluated MIMO controllers got almost identical daylight instead of a different day each. This enables a better comparison between the two controllers performance.

5.4.6 Energy savings by increased lifespan

From 2.1.5 it was found that the potential lifespan increase of the system in theory is mainly connected to the temperature of the LEDs. This is in turn depending on the power entering the diodes. The increase in lifespan is hard to determine. The energy saved by reduced production should however be negligible in comparison to the energy saved during use by implementing daylight harvesting, especially considering the long lifetime of LEDs.

5.5 Ergonomic considerations

From the SISO system it was found that the just noticeable difference value is valid and that a controller that was undetectable was possible to implement. An interesting thing found was that the occupants working in the room found the illuminance too bright when the setpoint was set to 500 lx. This might have to do with the reference sensor that was used for calibration being placed in a darker part at the corner of the workspace, meaning that the illuminance where the occupants were working was brighter.

6

Conclusions and future work

In this chapter the conclusions from the thesis is presented, as well as possible future work in the subject.

6.1 Research questions

In this section the research questions formulated in section 1.3.1 are answered.

6.1.1 Illuminance control

As stated in 2.1.2, a completely constant illuminance is not necessary, as changes under 7.4% in illuminance is undetectable for most people. A controller that does not consistently change the illuminance more than 7.4% of the initial value is therefore sufficient, and as shown in the results, is possible to achieve.

For a SISO system an I-regulator on the form described in 3.2.2 is suitable for control, it is easily implemented and does not require much calibration. Meanwhile it is fully capable of following changes in daylight closely, except for when daylight is quickly blocked, and keeps the illuminance constant enough to be undetectable.

For a MIMO lighting system both the LQR and LP-controller described in section 3.6 was found to work well for controlling illuminance. The difference in performance was small. The main difference between the two is that the LQR stabilises the zone illuminances spread out around the setpoint when it is not possible to reach the setpoint for all of the zones, while the LP-controller guarantees that the estimated ground illuminance is at or above the setpoint. Which of these to choose for a lighting system therefore depends on what one wishes for the setpoint to mean. If the setpoint is a minimum illuminance requirement the LP-controller is a good choice, although the setpoint might have to be increased slightly from the requirement due to possible errors in estimation. If one wishes for all illuminances to be as close as possible to the setpoint the LQR is the better choice. The LQR is also much less computationally expensive, which might be important to consider. Both controllers are fully capable of keeping illuminances constant enough to not be detectable, except when there is a rapid change in daylight.

6.1.2 Energy savings

The energy savings test for the SISO controller lead to an extrapolated approximation of 20% as compared to an uncontrolled lighting system, on the chosen day in the office where the controller was operating. A simulated perfect SISO controller on the same daylight profile used for the energy tests of the MIMO controllers achieved 46% energy savings. However, for the MIMO controllers there was also a small amount of extra ambient illuminance added, which means the energy savings for those are a slight overestimation. The energy savings tests for the LQR and LP-controller for the MIMO system found that they respectively saved 49% and 53% energy as compared to an uncontrolled system when the chosen daylight profile was used on the system. As discussed in section 5.4.6, the energy savings from a potential increase in lifespan could not be retrieved in this thesis, however, it is fair to assume that the lifespan of LEDs is increased when dimmed, the absolute amount of energy saved from this should however be negligible in comparison to the amount of energy saved during use when a daylight harvesting control system is implemented.

6.2 Future work

There are two major areas that might be interesting for further evaluation. Illuminance estimation, and the possibility of implementing Robust control theory and more automatic tuning on the systems.

6.2.1 Illuminance estimation

During this project the subject of illuminance estimation was never in the absolute focus and the method used is very basic. It would be of major interest to evaluate different methods of approximating the illuminance levels using other methods than a direct linear transform. Examples that might be of interest is using a Camera and Machine Learning as well as different methods of measuring the daylight. For example measuring the daylight directly at the entry point and using this approximating the illuminance in different control zones.

6.2.2 Robust and advanced light control

A robust lighting control system as well as looking for more advanced methods to tune the systems to a desirable level would also be an interesting area to explore. A robust controller might be able to be created that works in many similar systems. This might in some way also solve the tuning problem.

An automated way of tuning the system would also be interesting to evaluate since all the methods implemented in this thesis were hand tuned by the authors. This might for example be done by placing several reference sensors on multiple workspaces with the ability to communicate with the central controller so that the controller could build all necessary matrices from simultaneous measurements.

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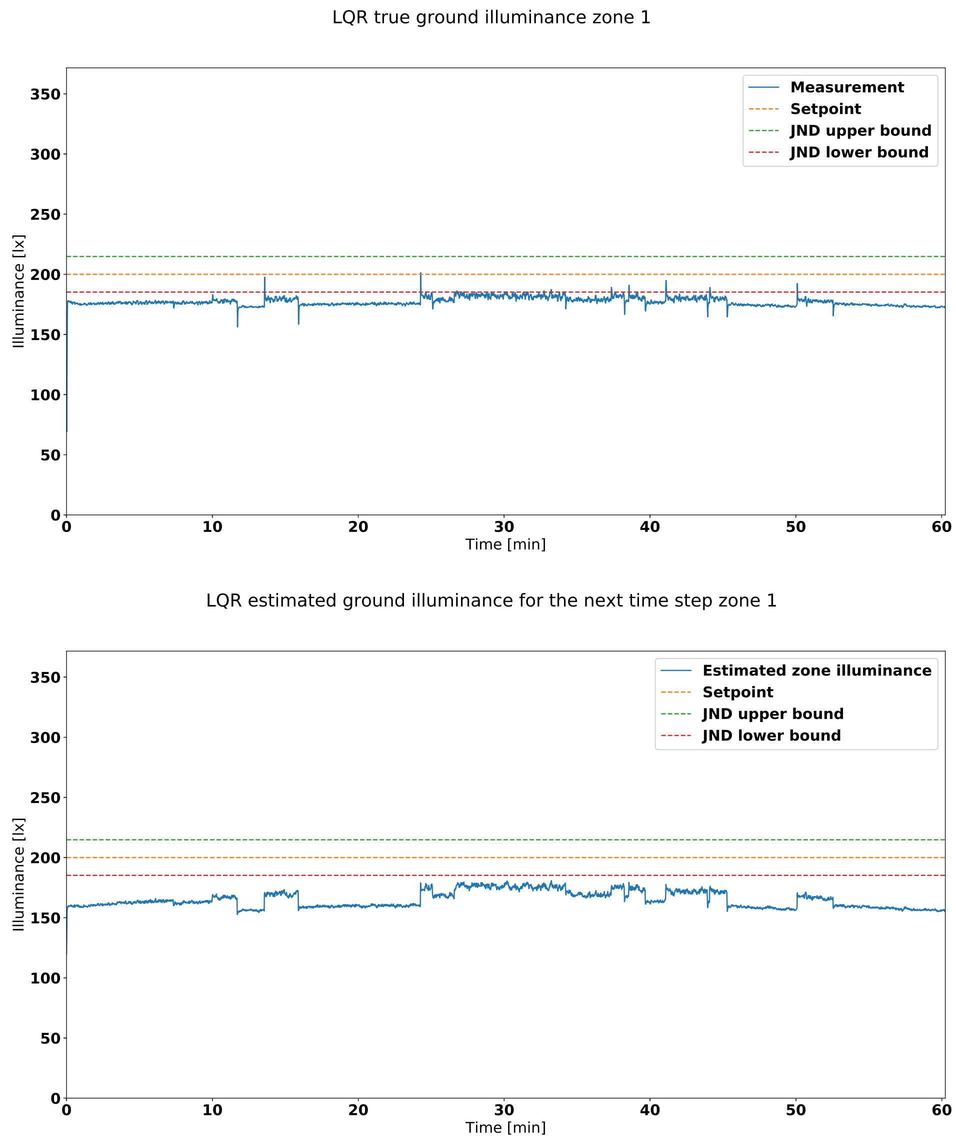
Appendix 1

A.1 Performance test: LQR of ground illuminance all zones



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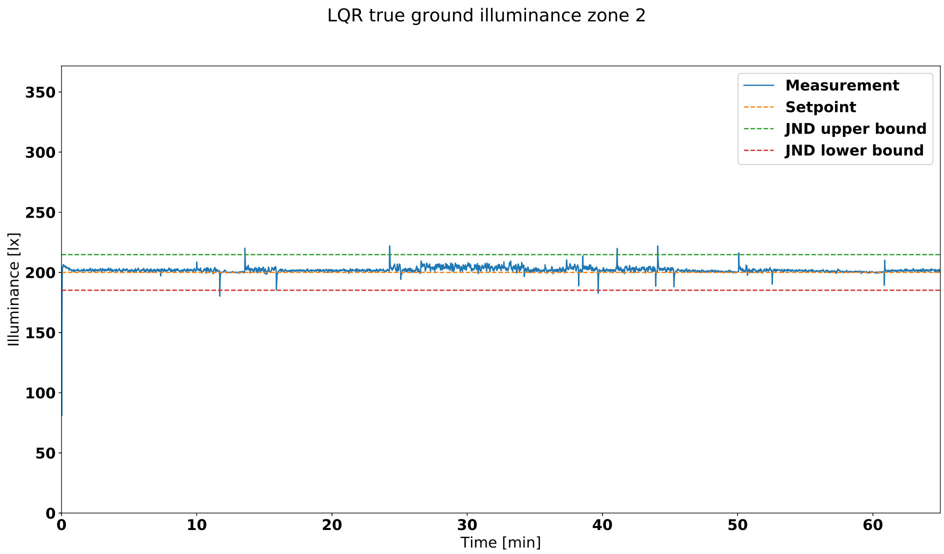

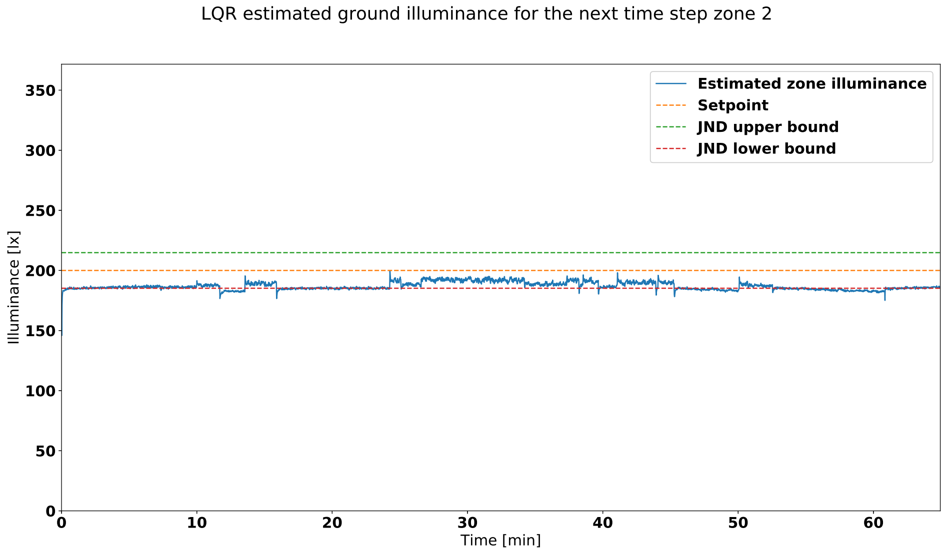

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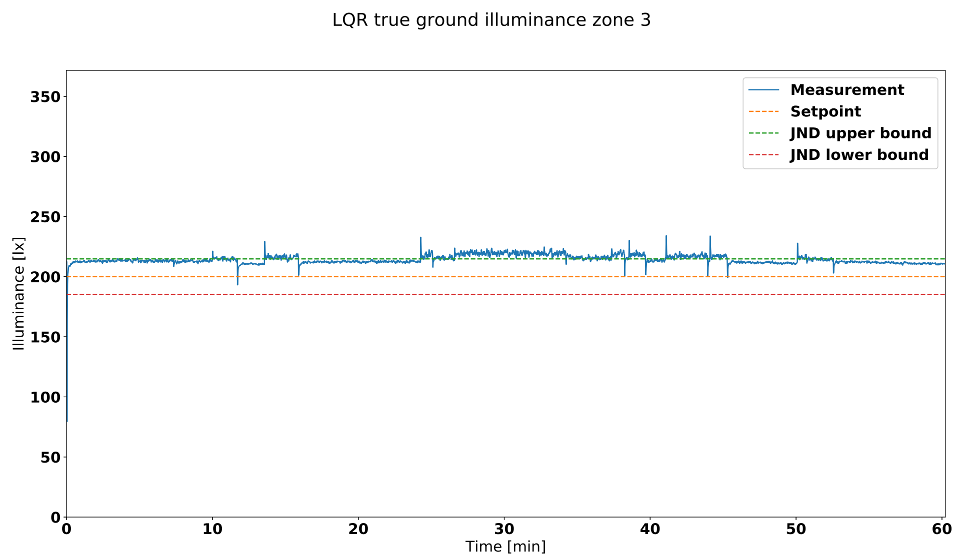

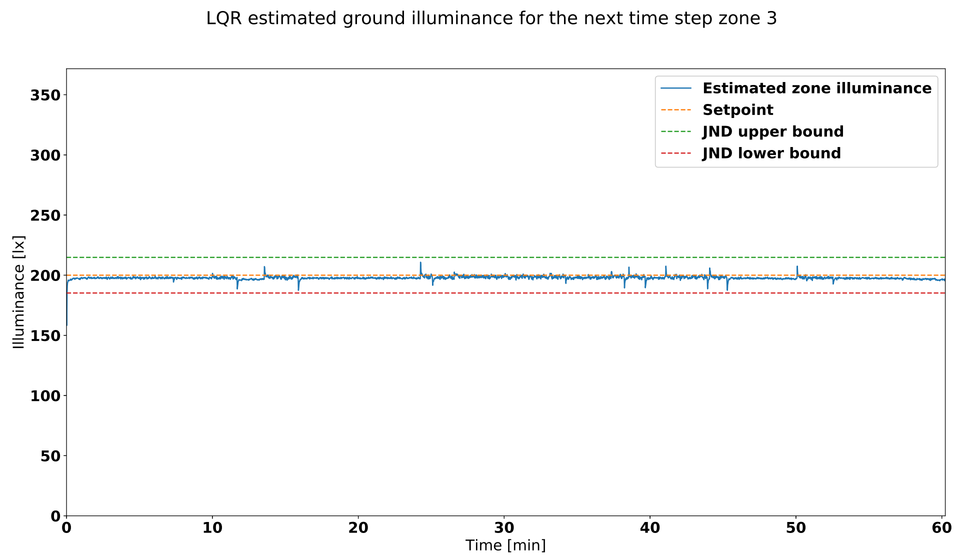

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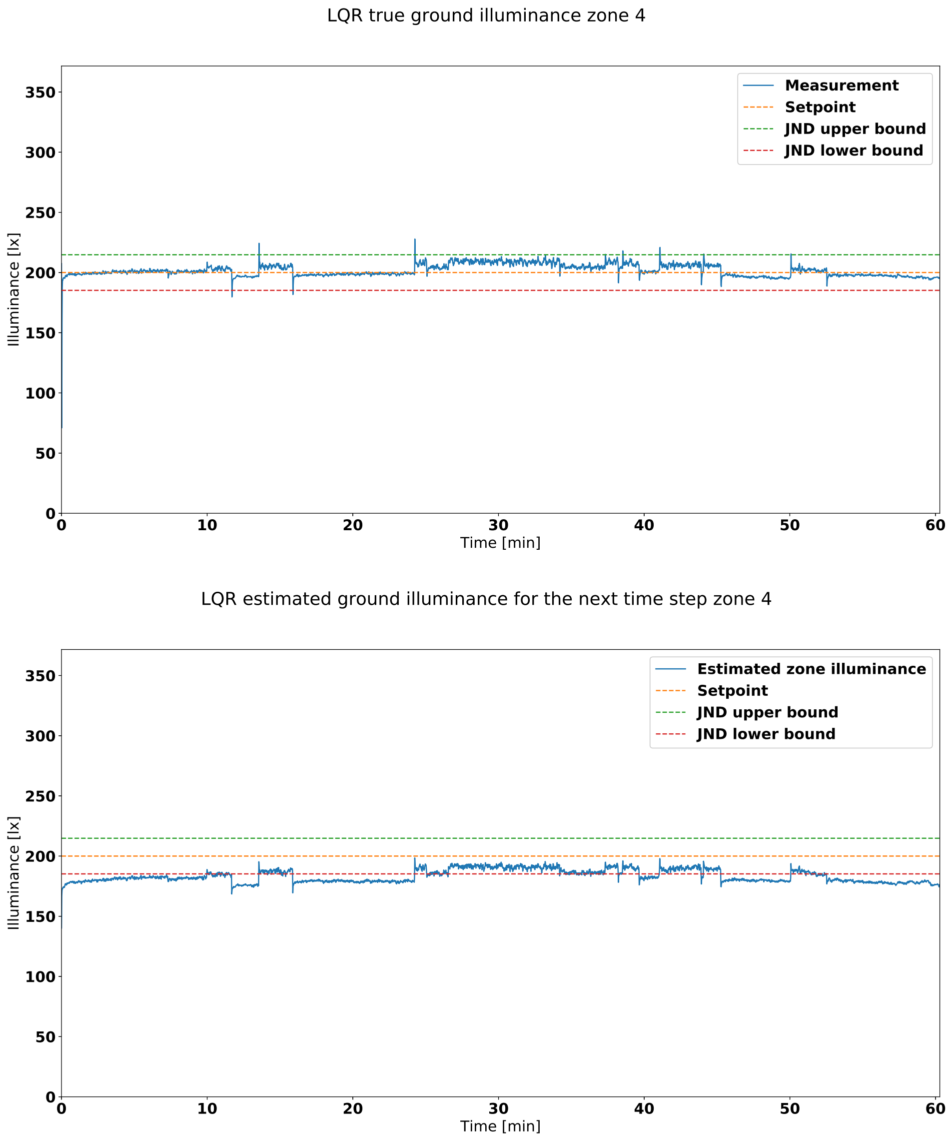

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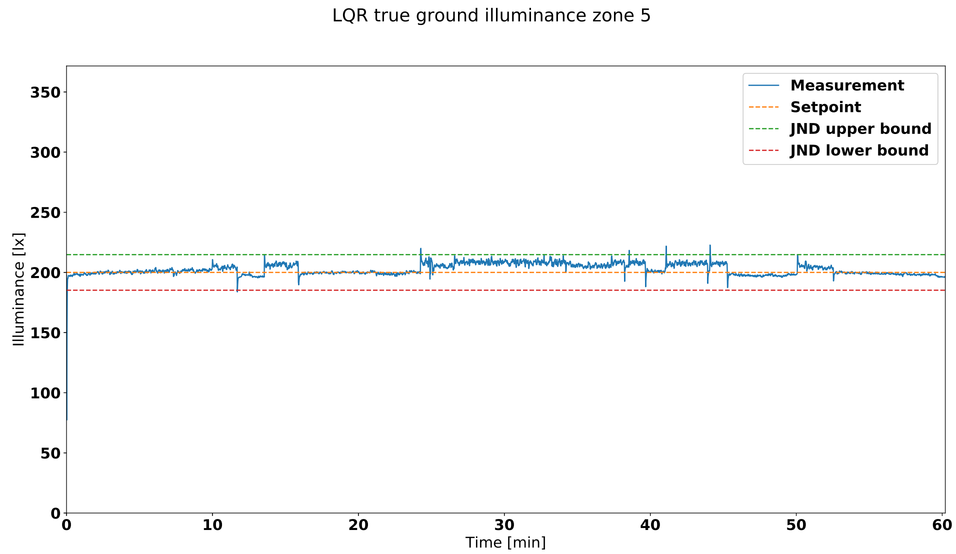

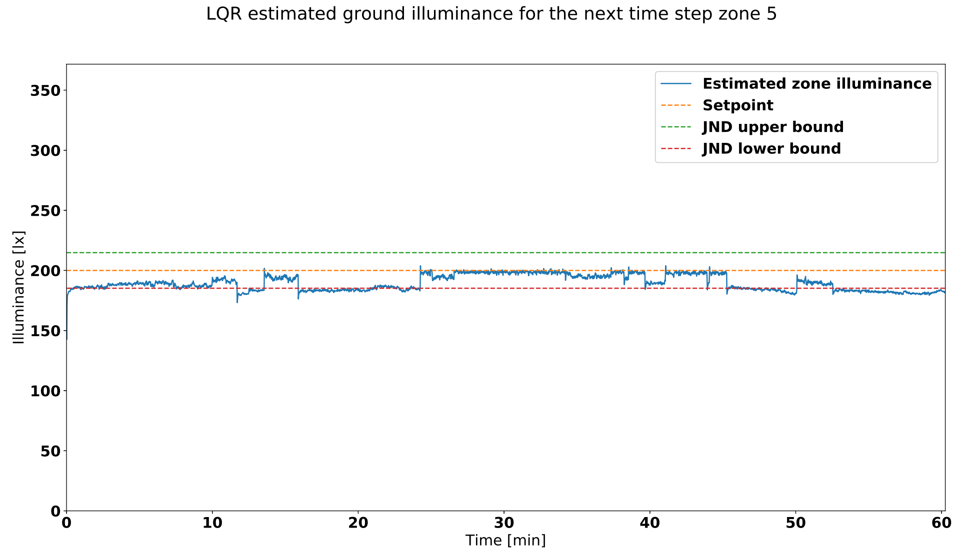

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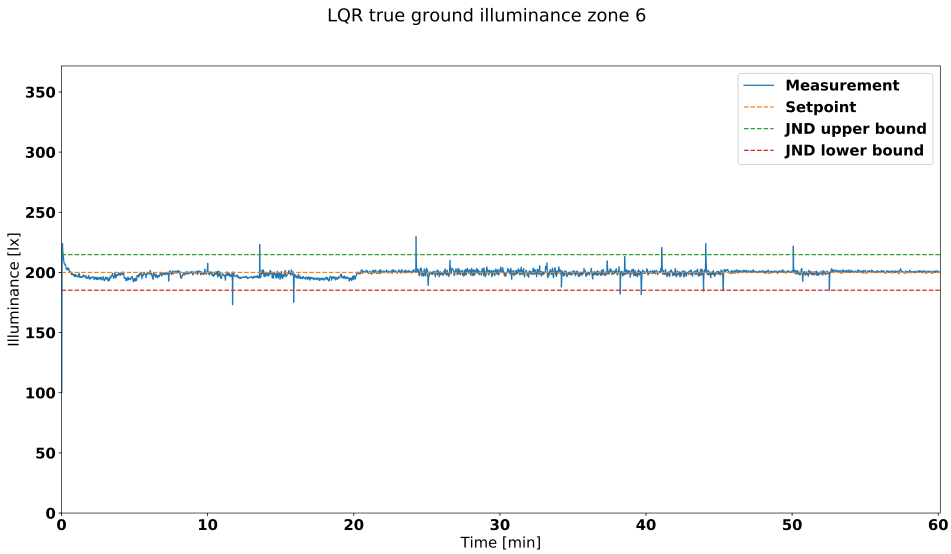

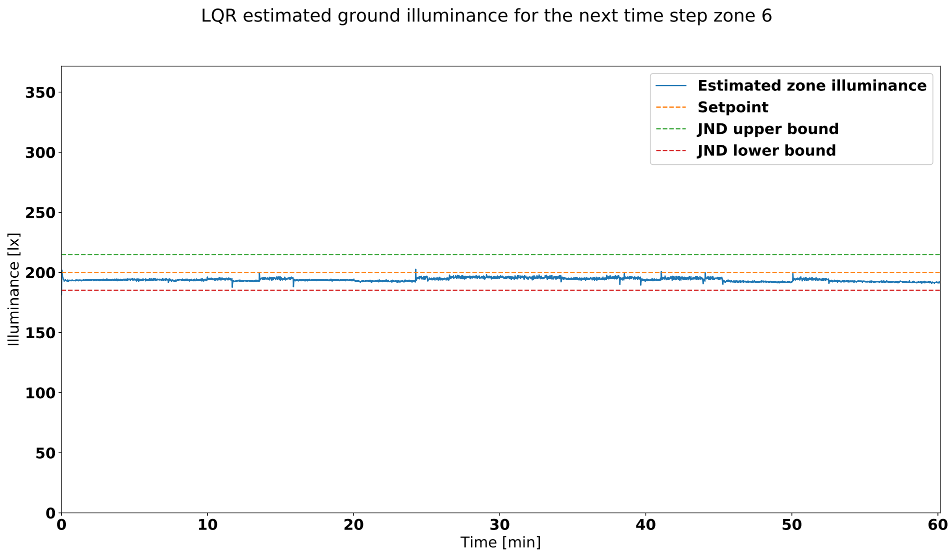

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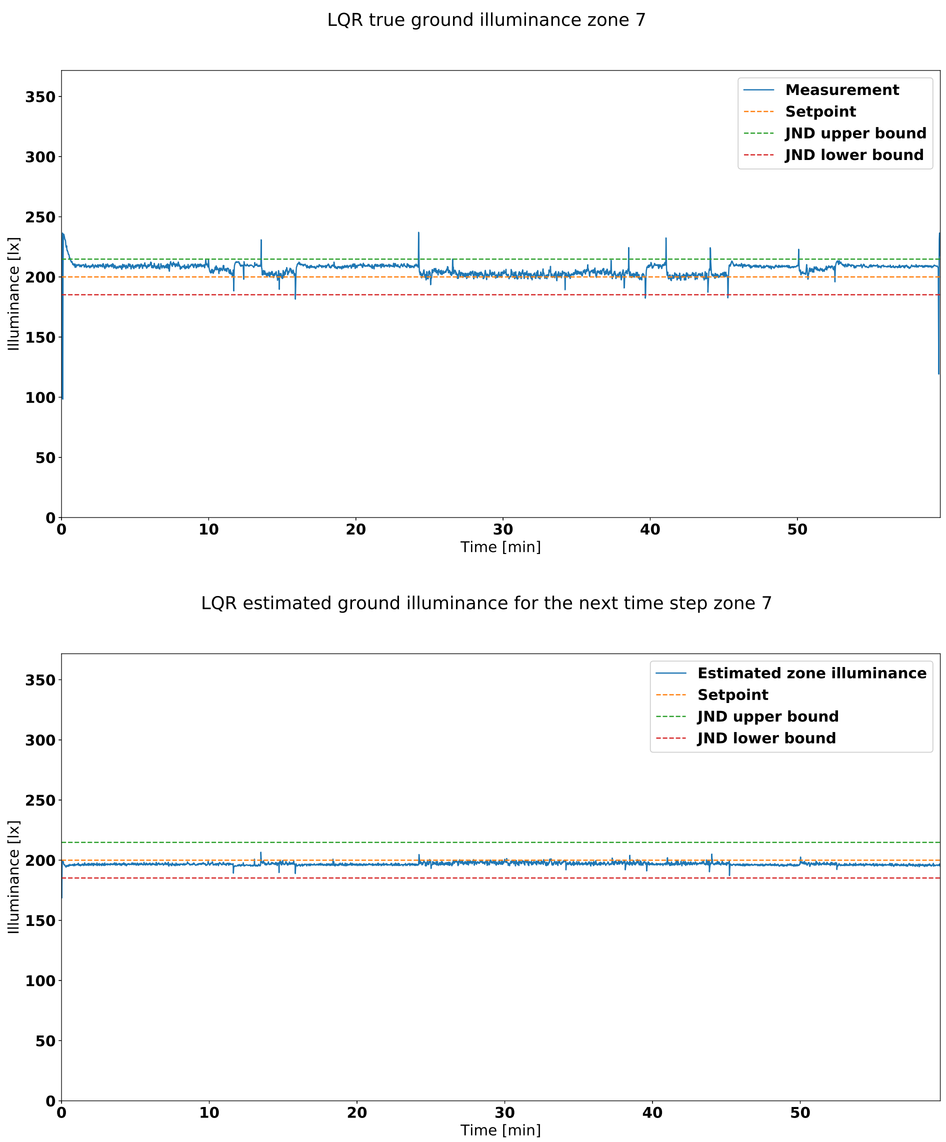

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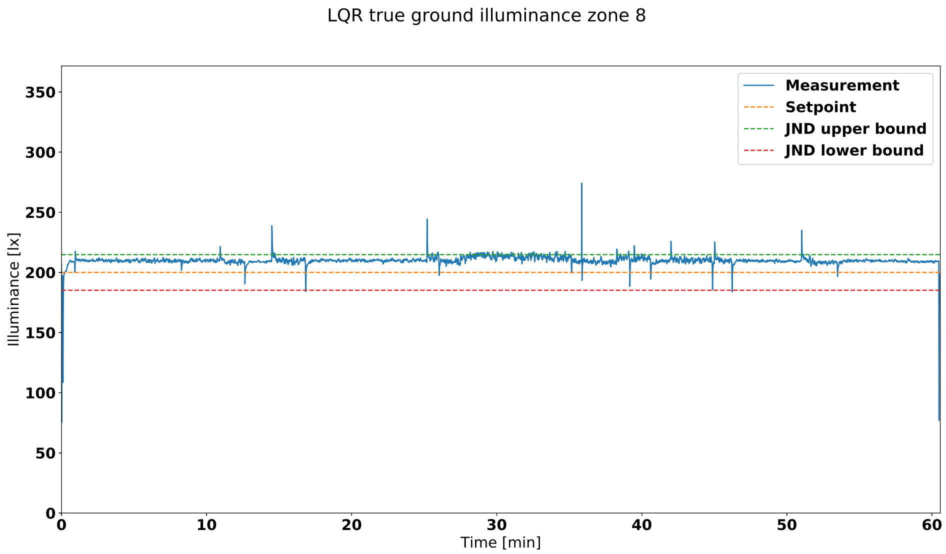

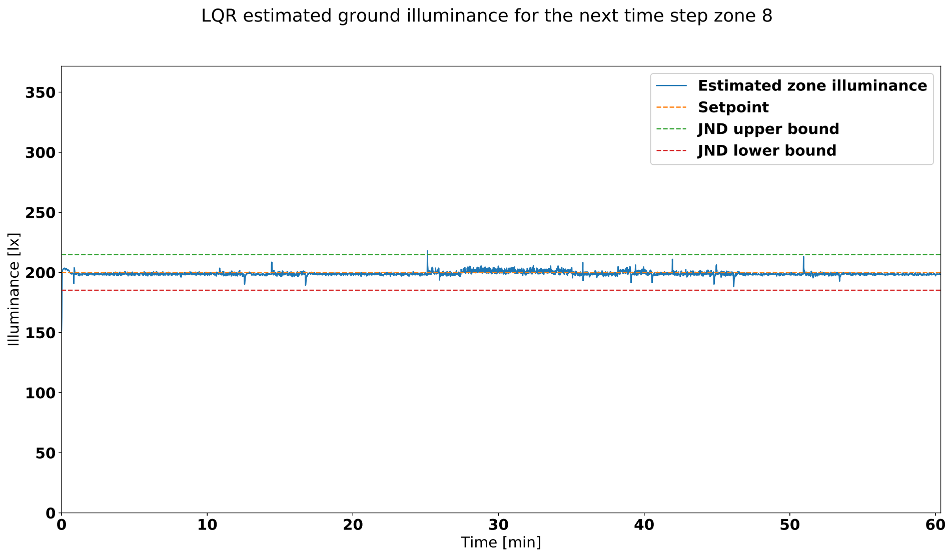

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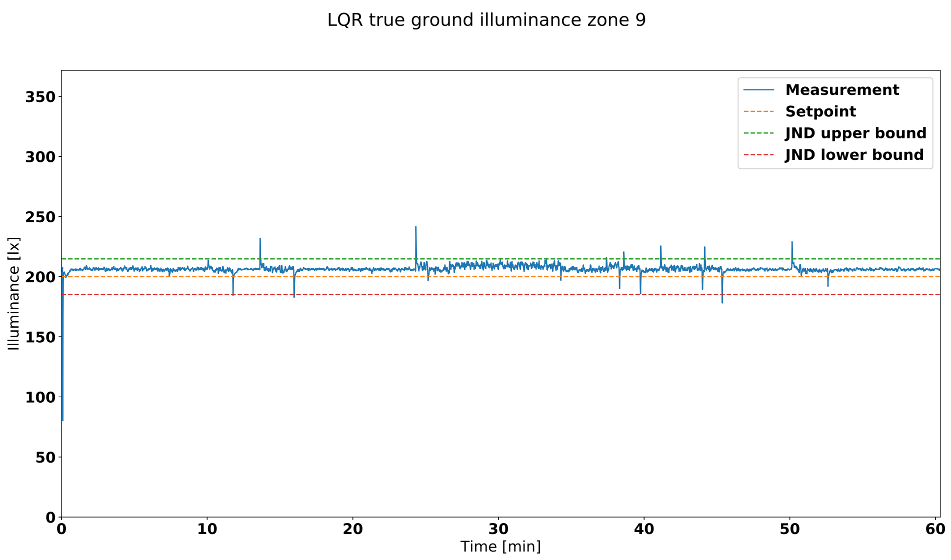

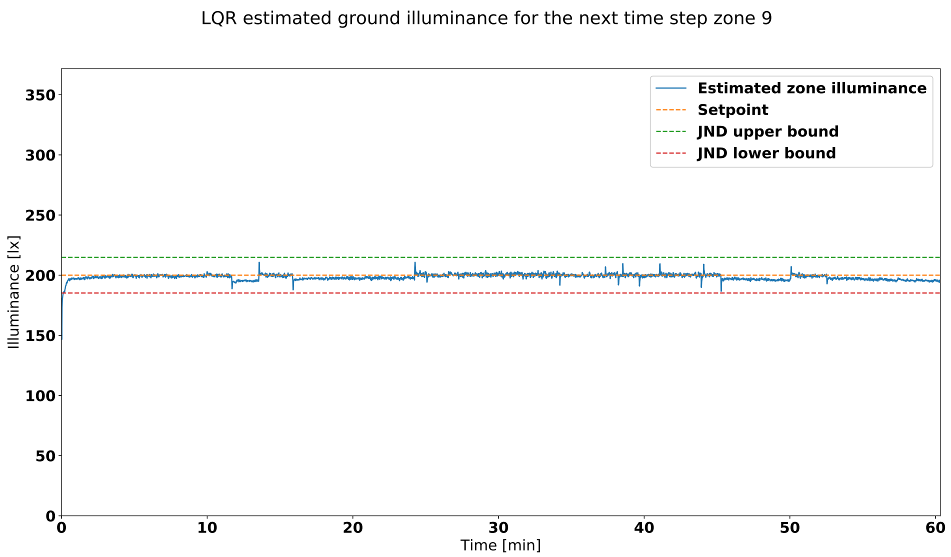

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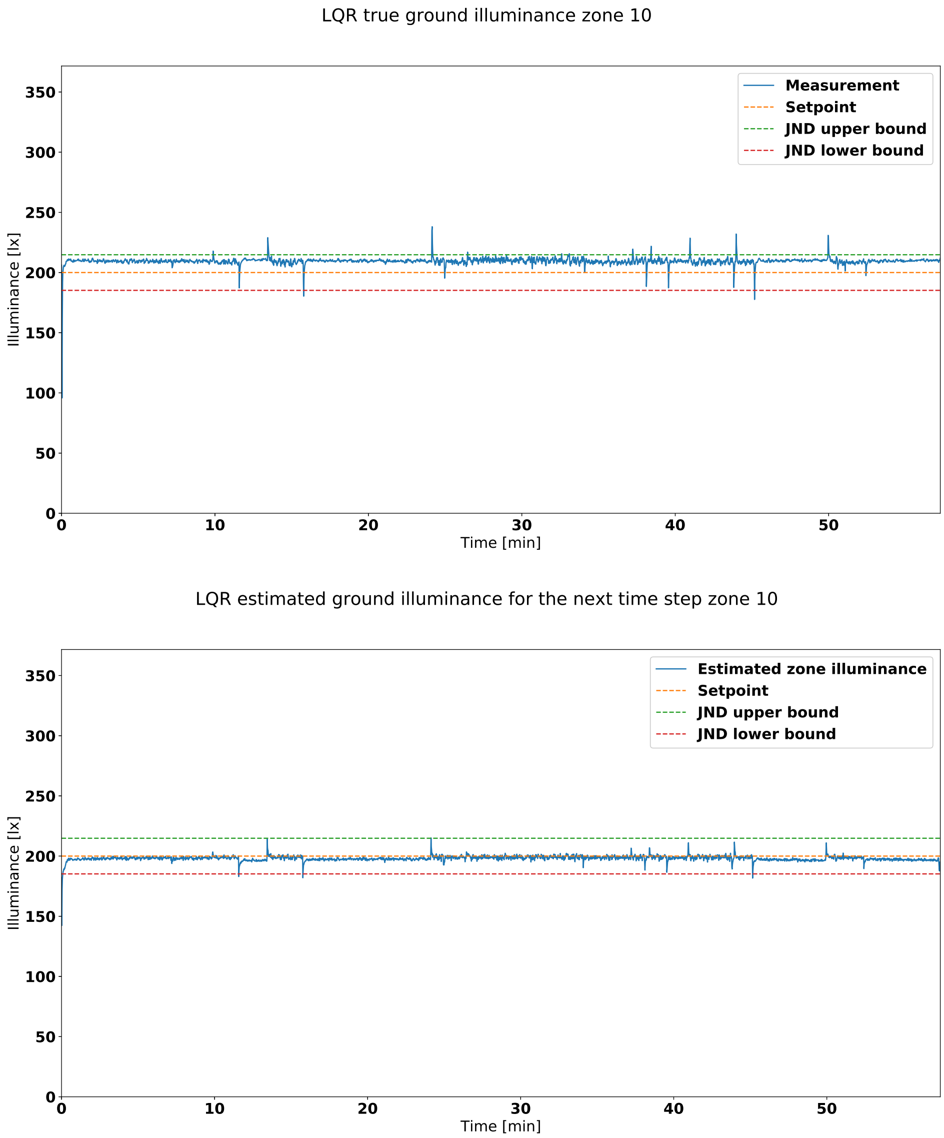

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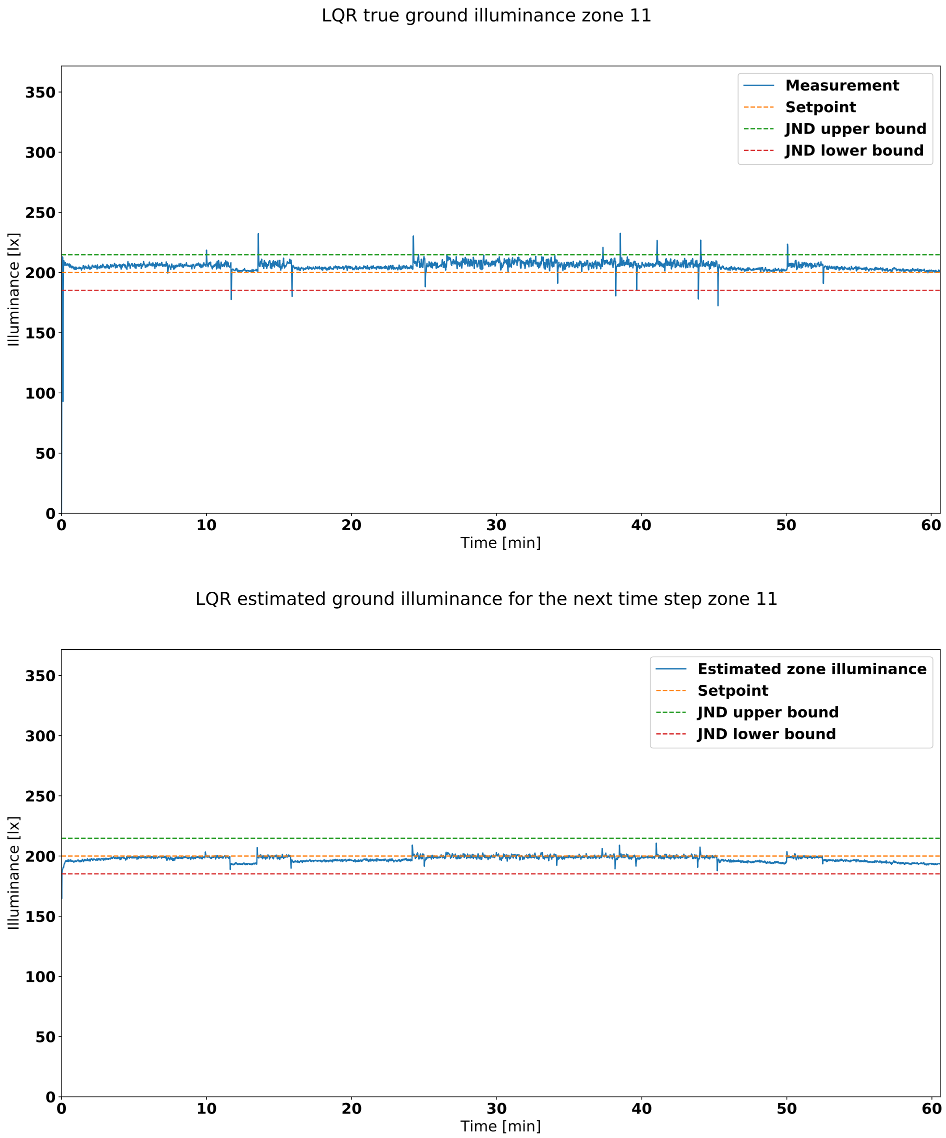

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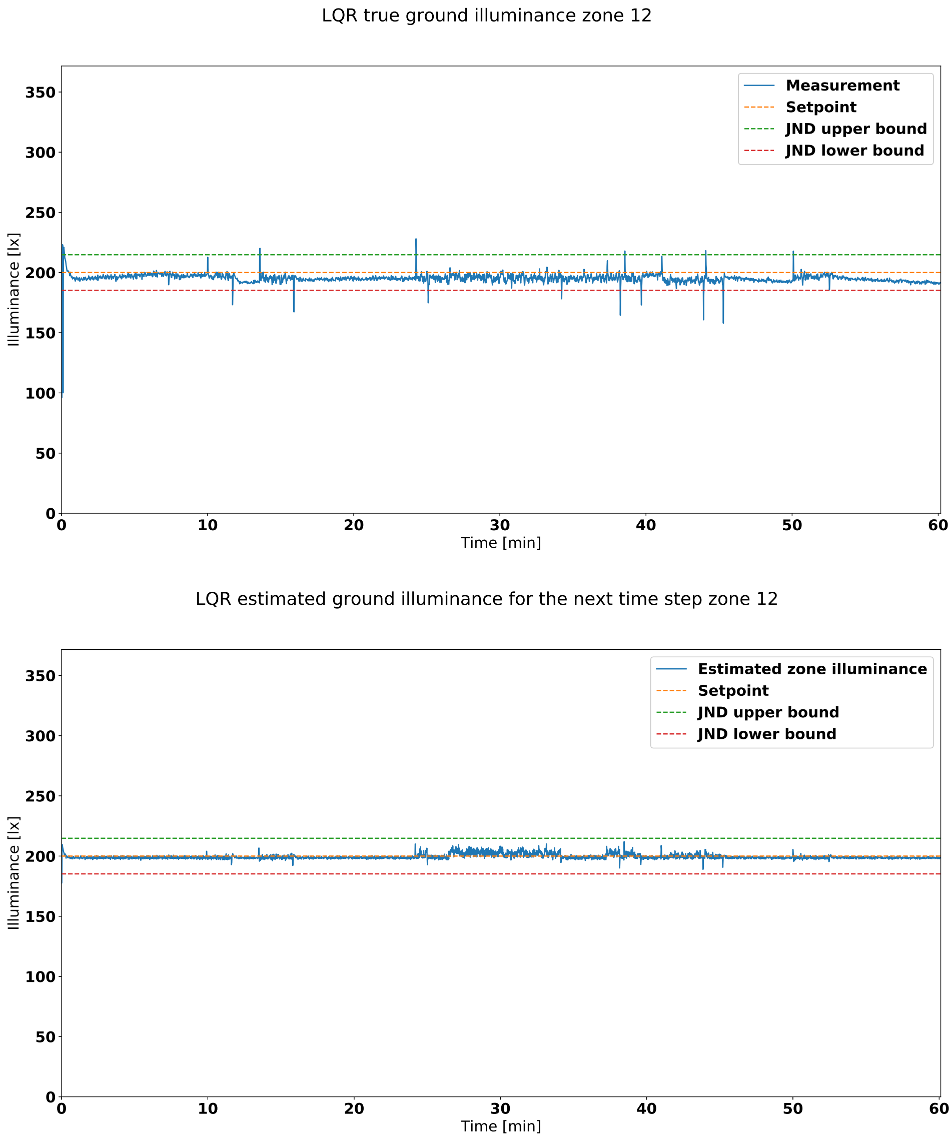

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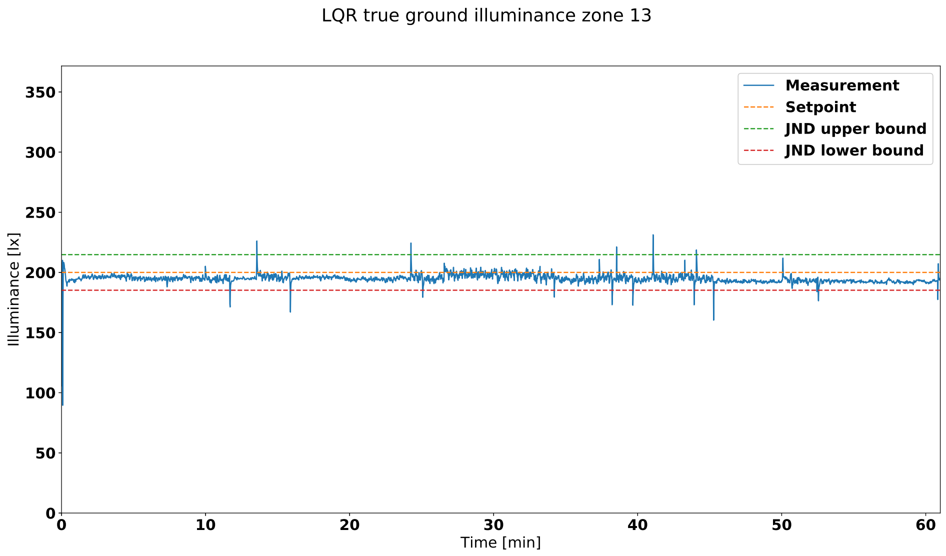

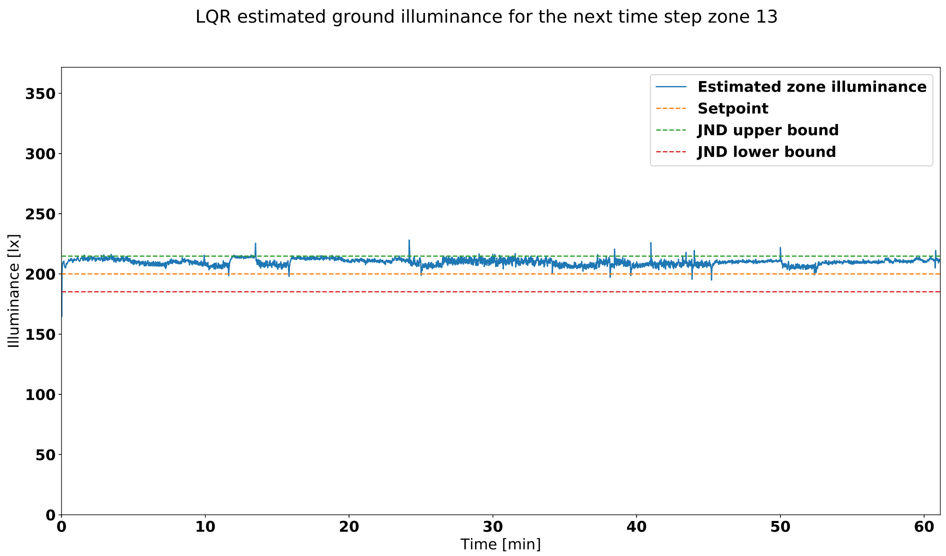

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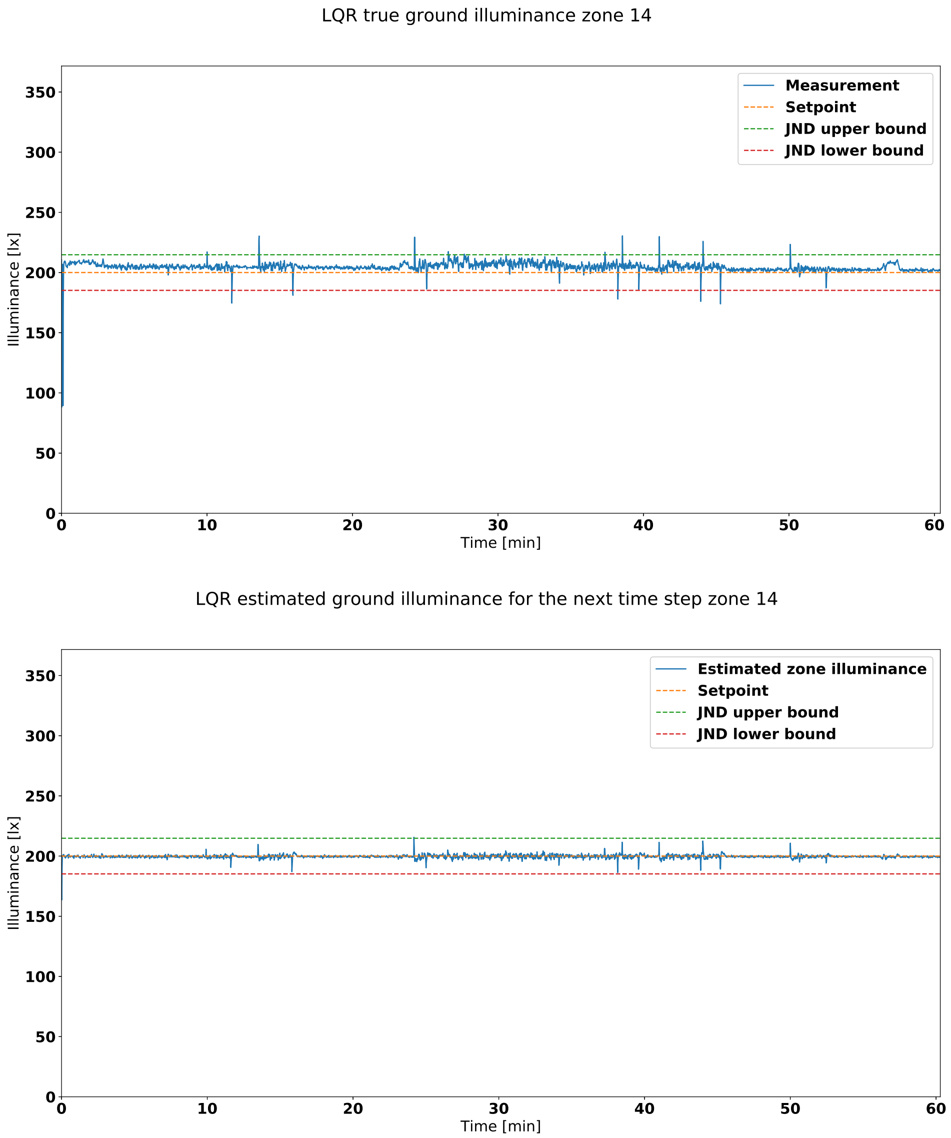

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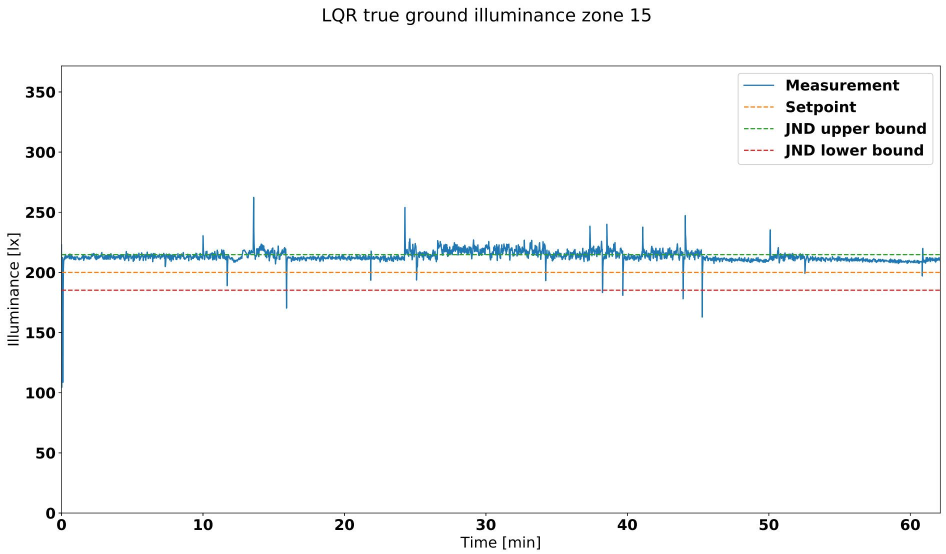

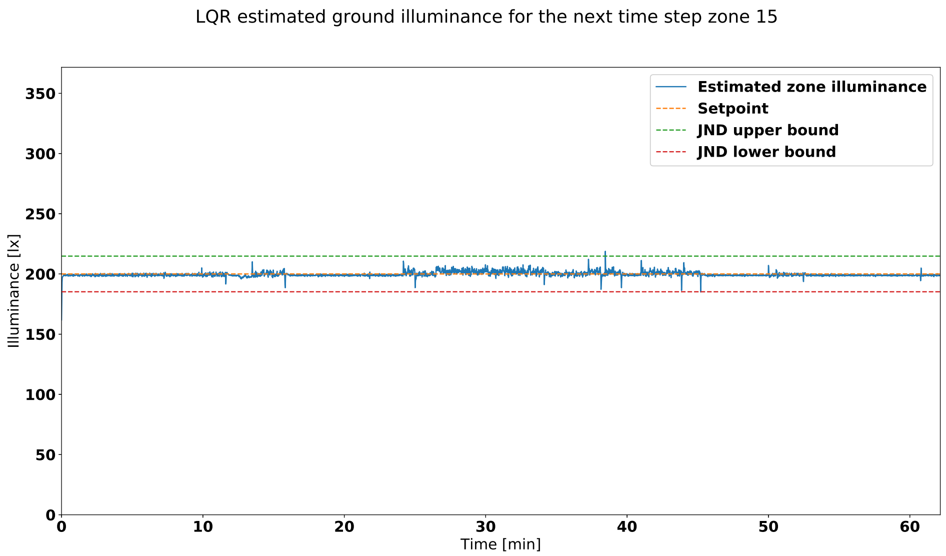

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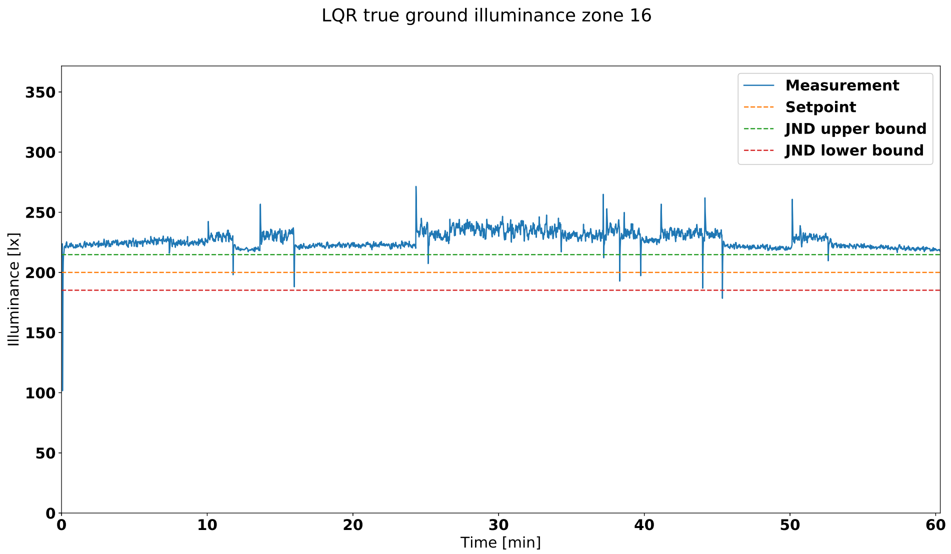

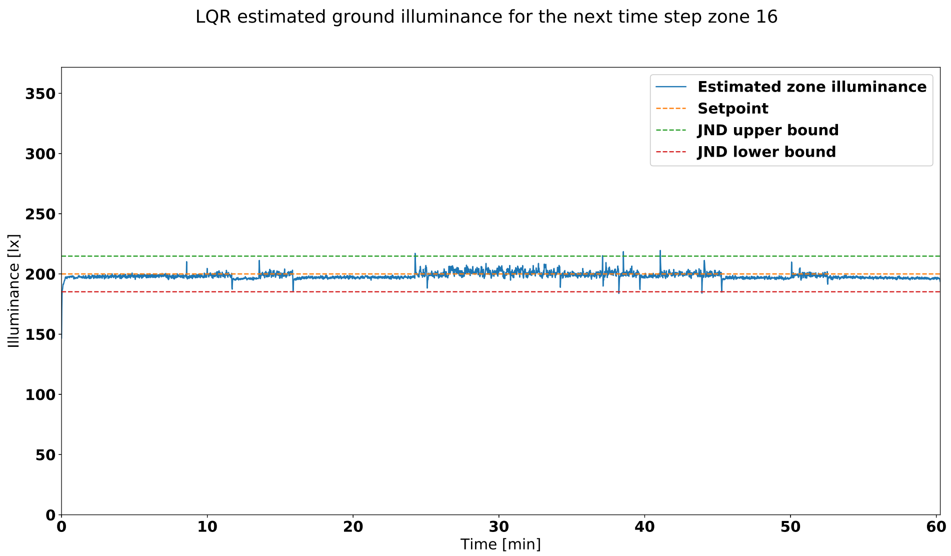

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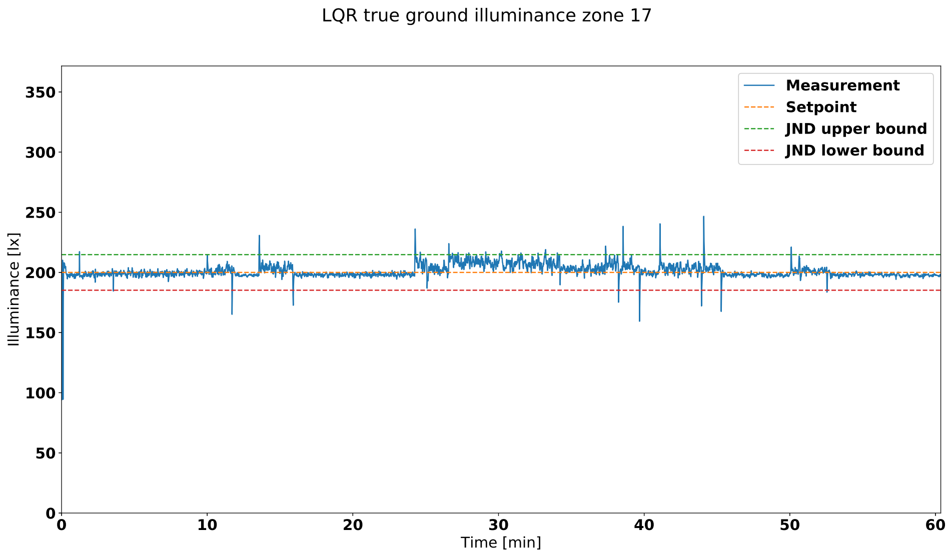

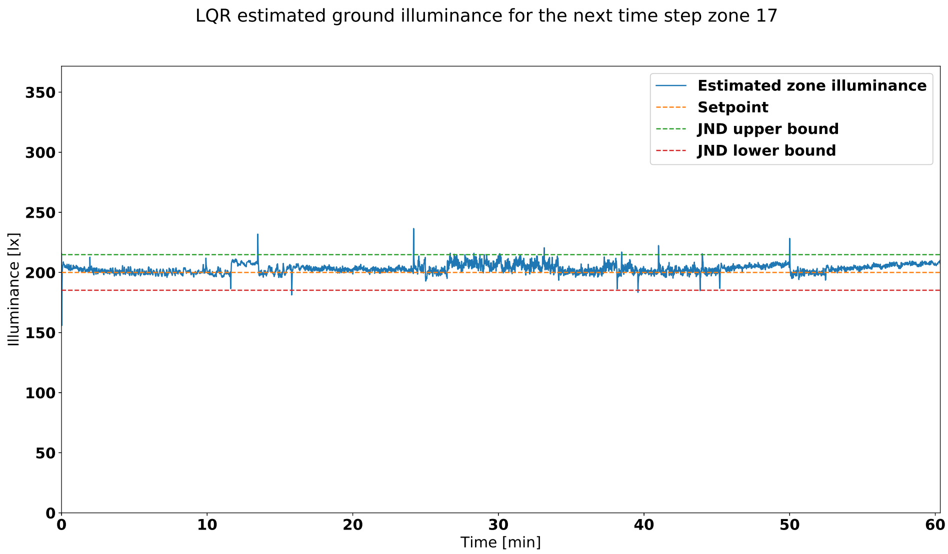

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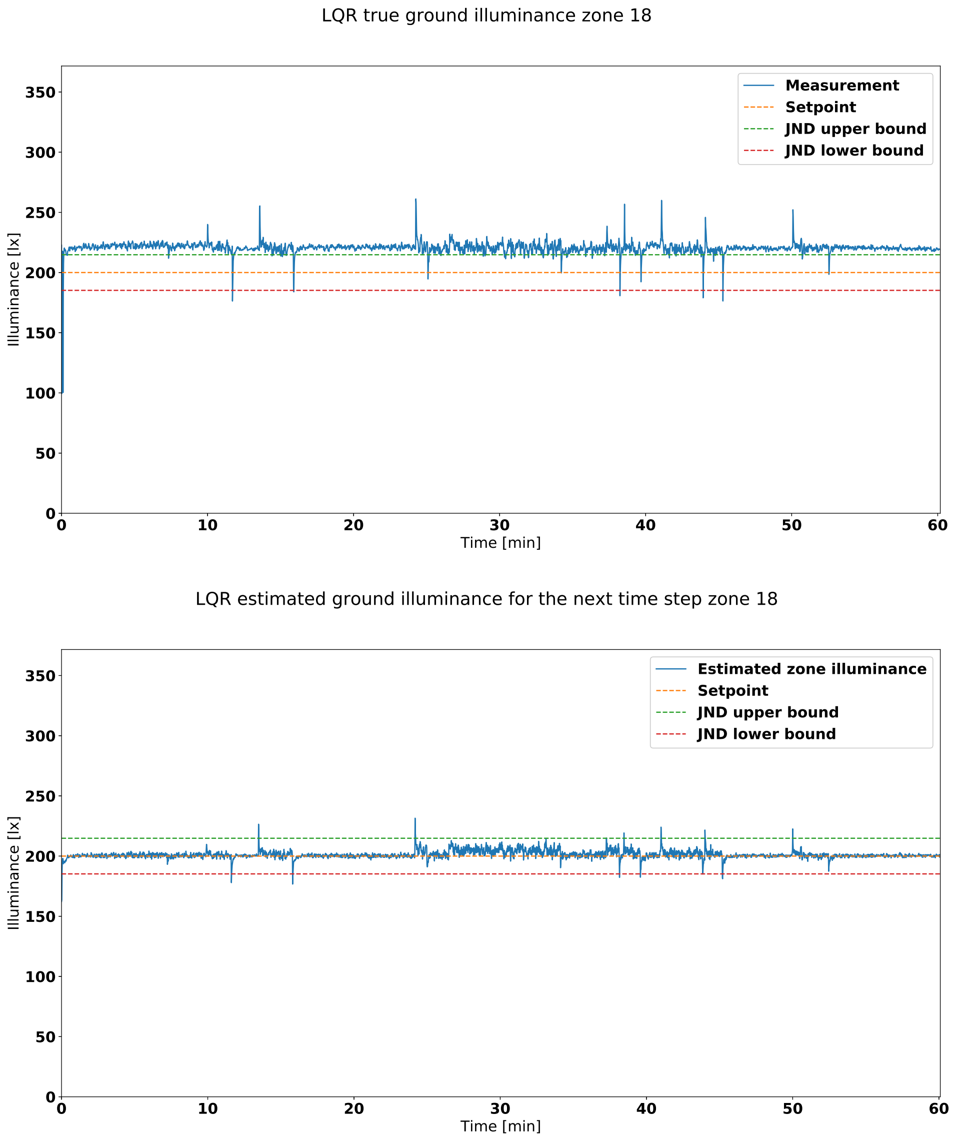

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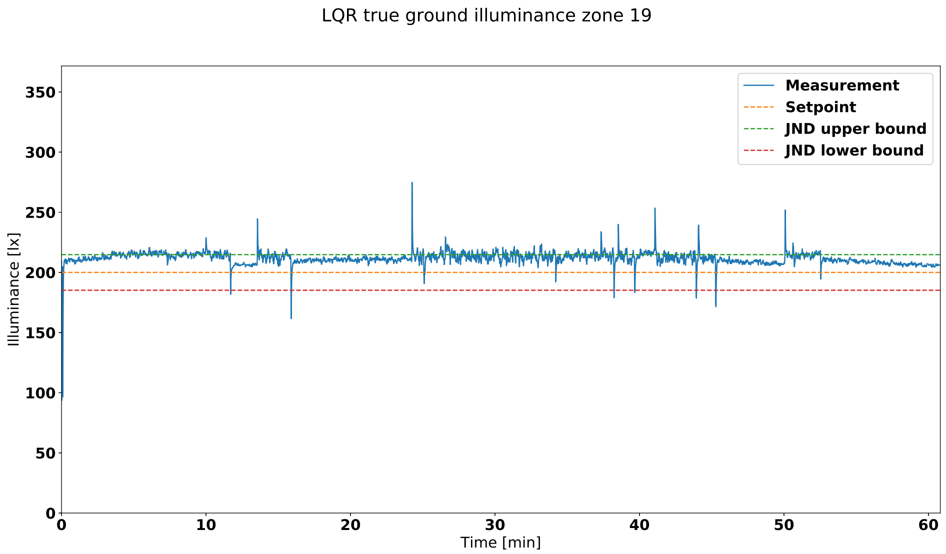

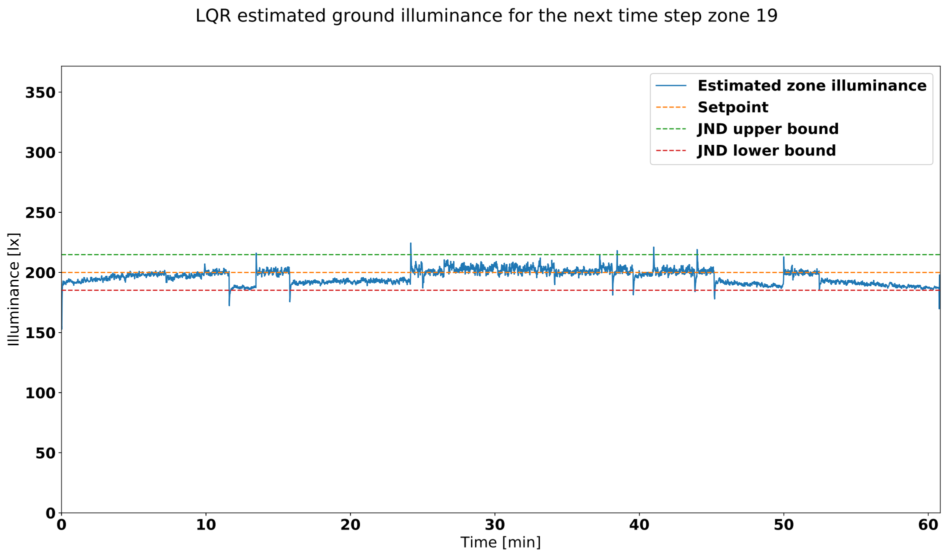

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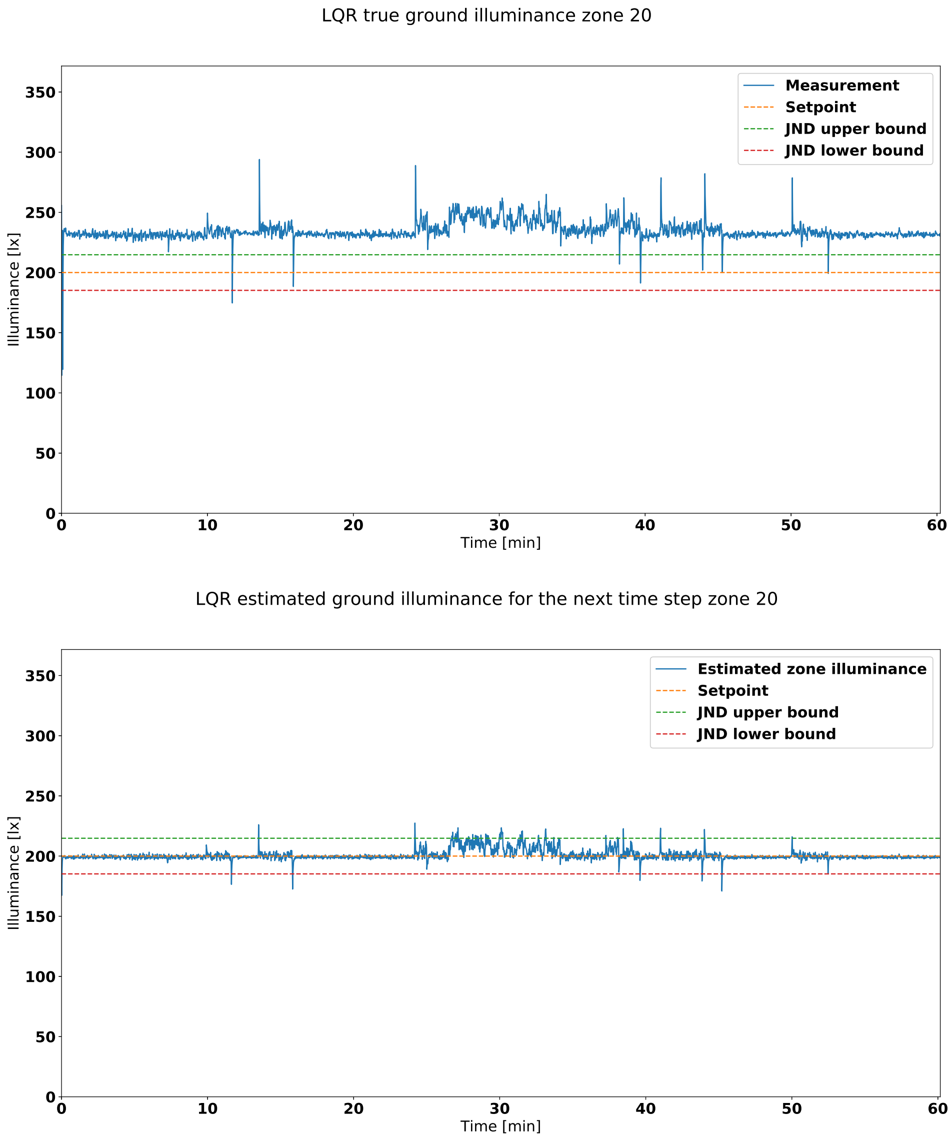

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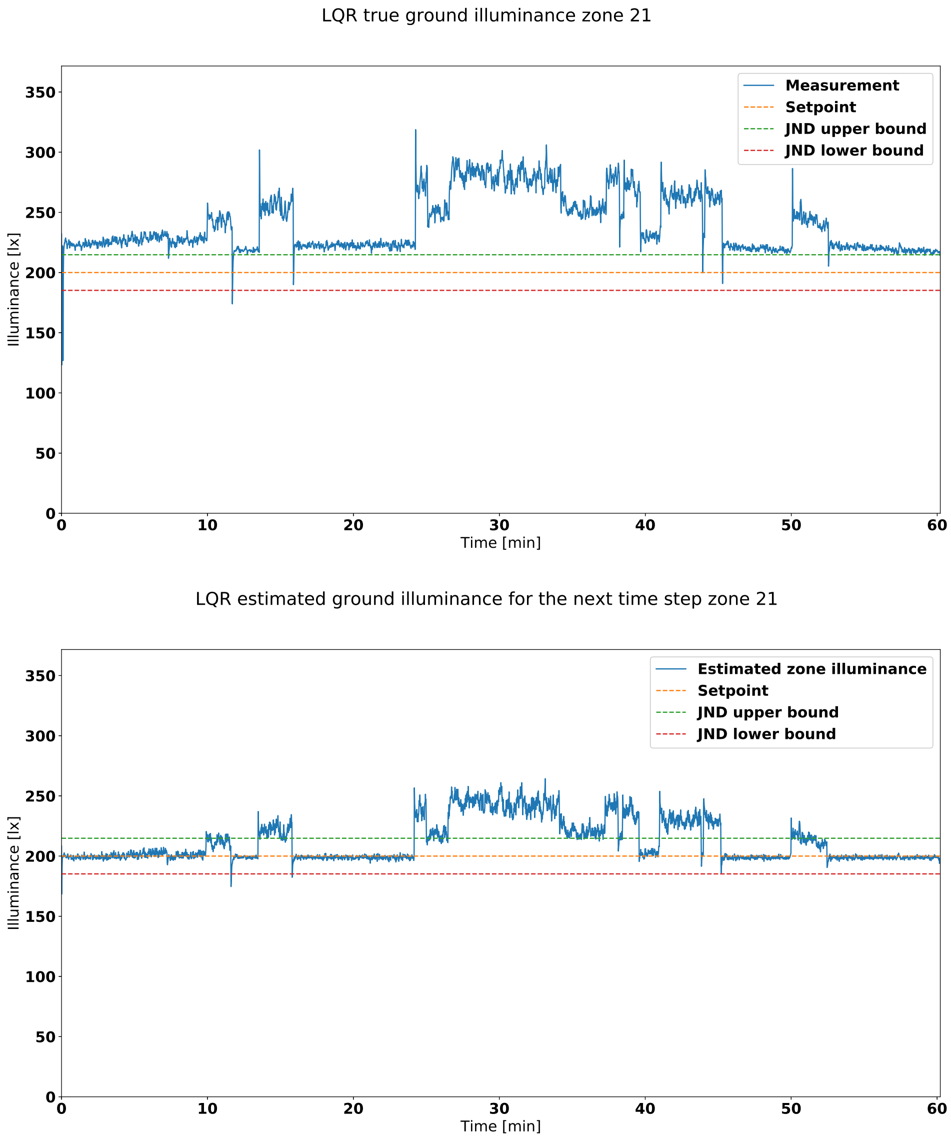

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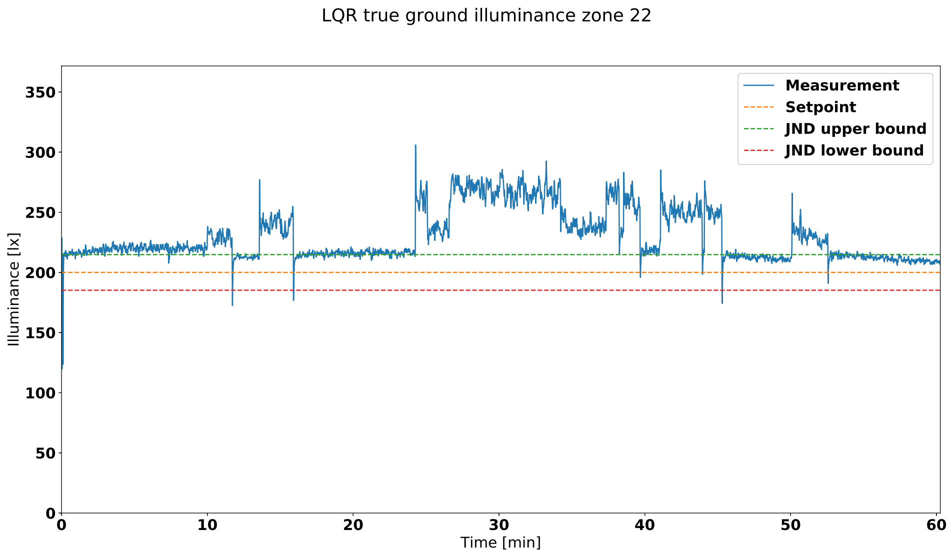

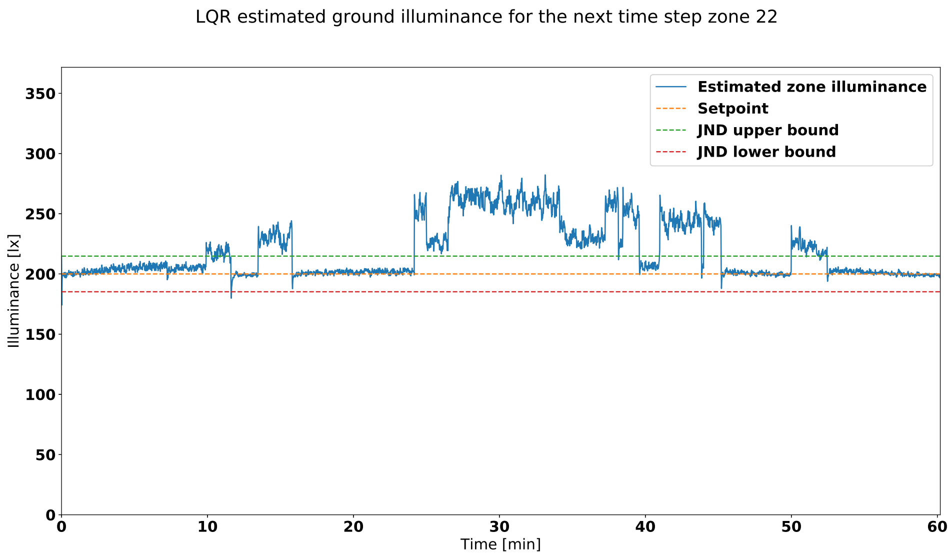

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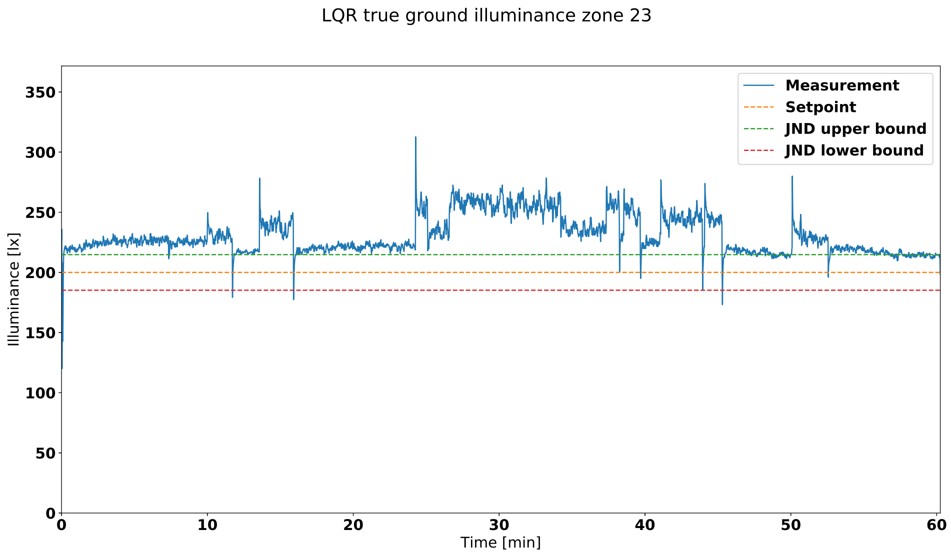


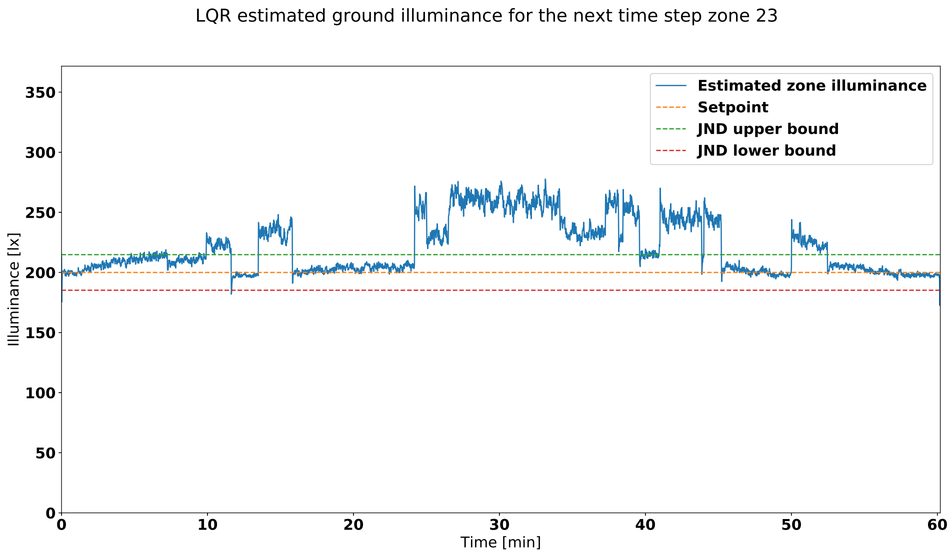


Figure A.23: Zone 23

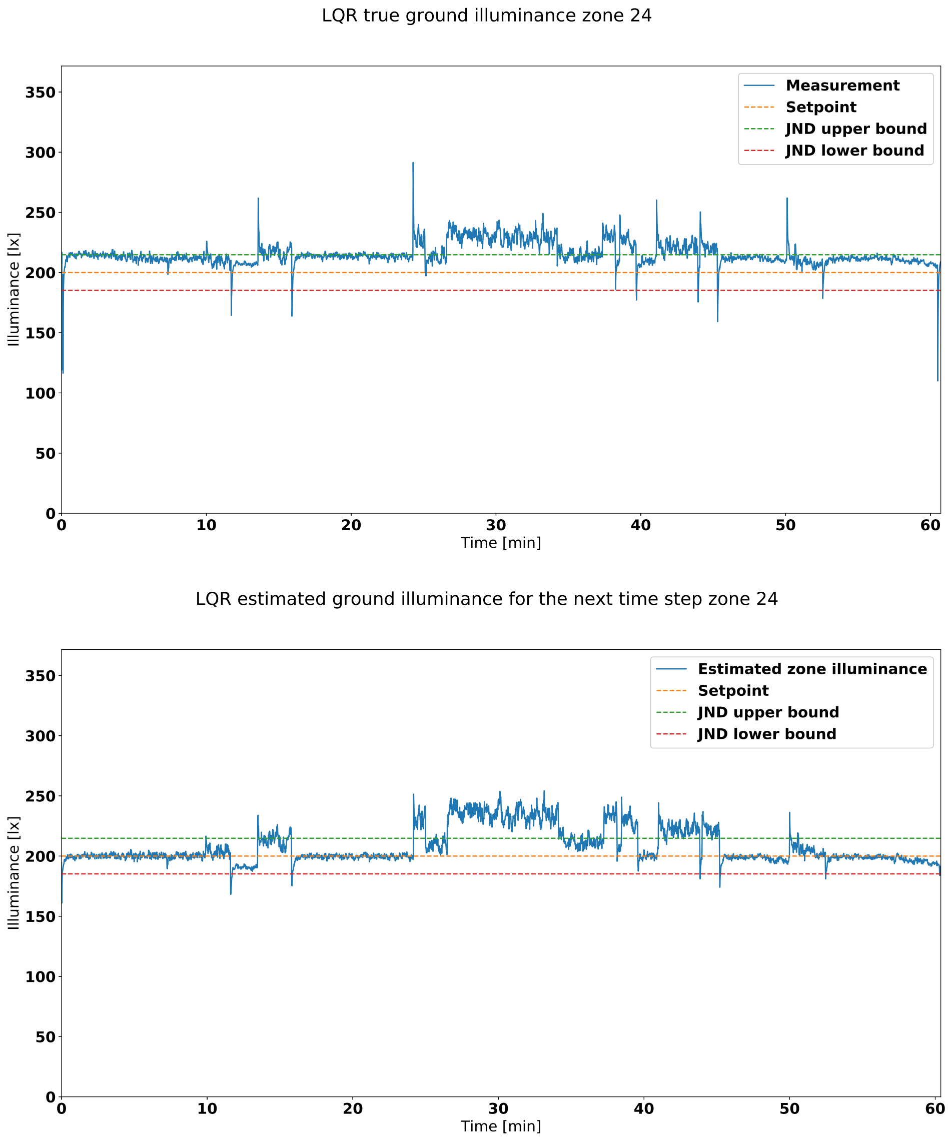
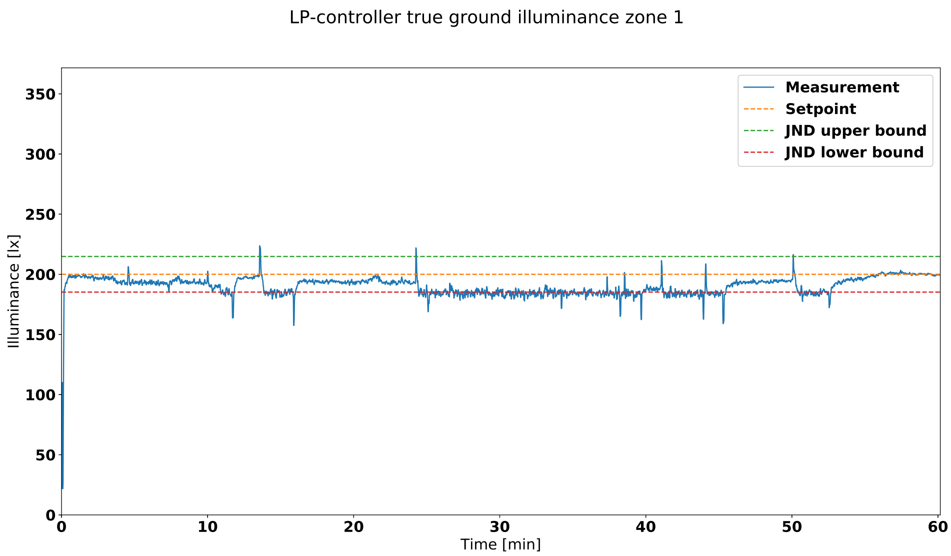


Figure A.24: Zone 24

A.2 Performance test: LP-controller of ground illuminance all zones



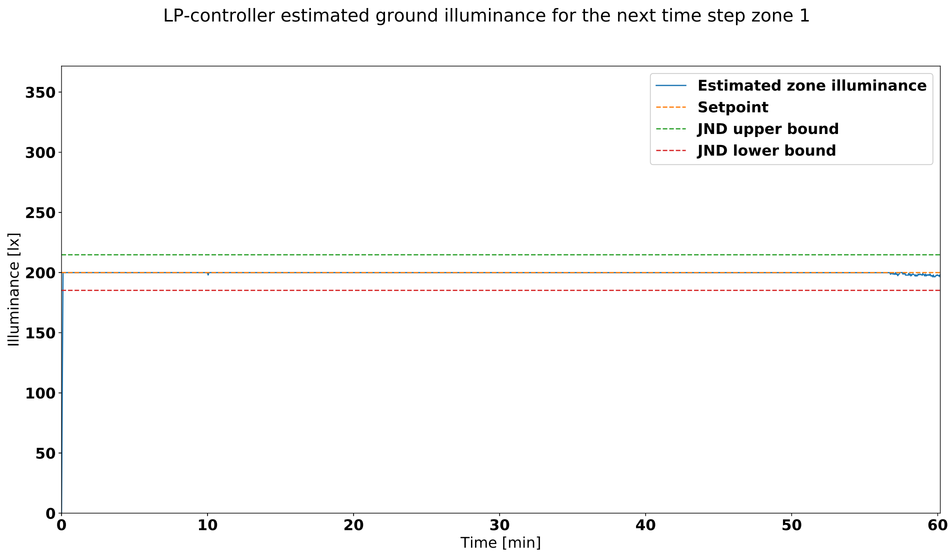


Figure A.25: Zone 1

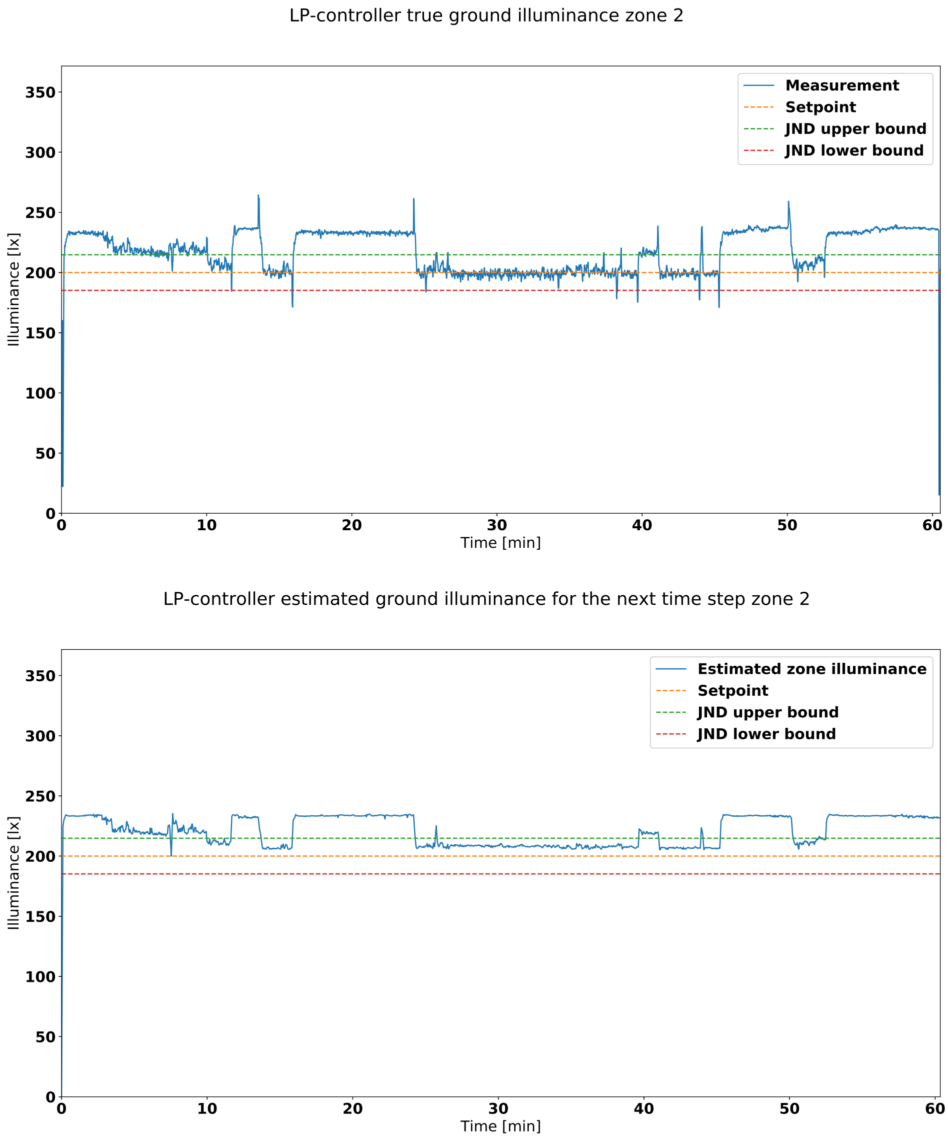
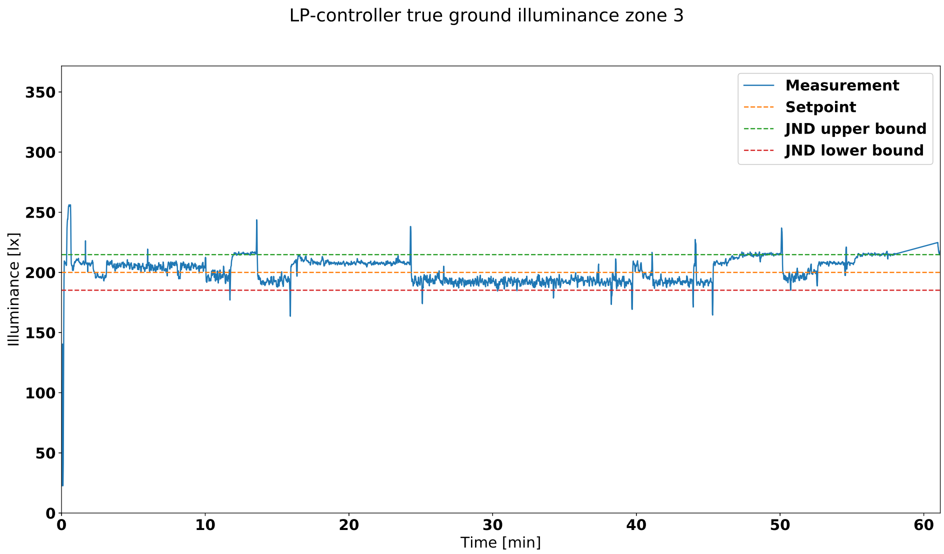


Figure A.26: Zone 2



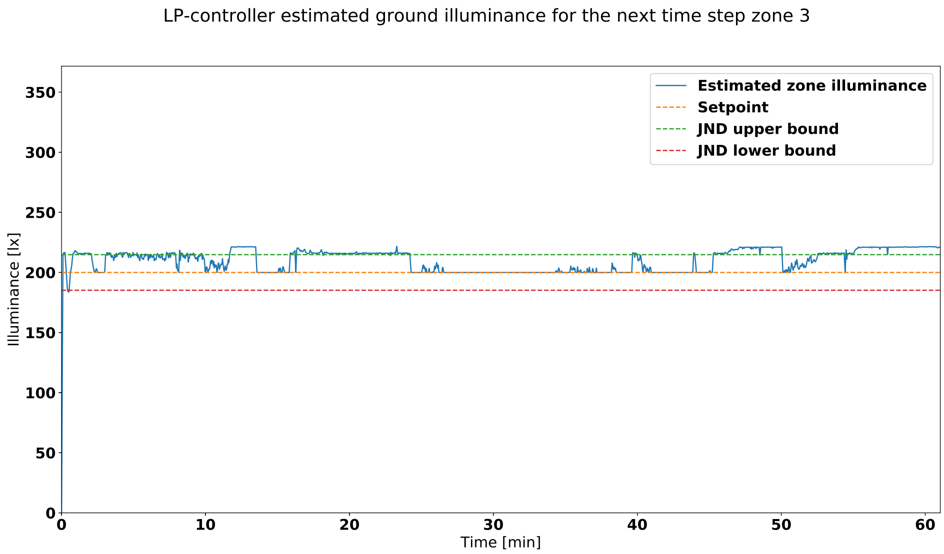
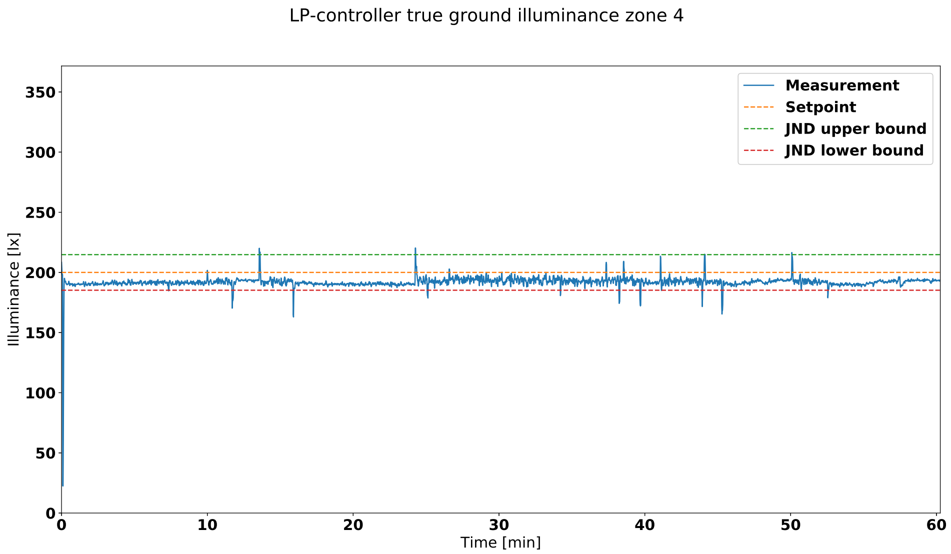


Figure A.27: Zone 3



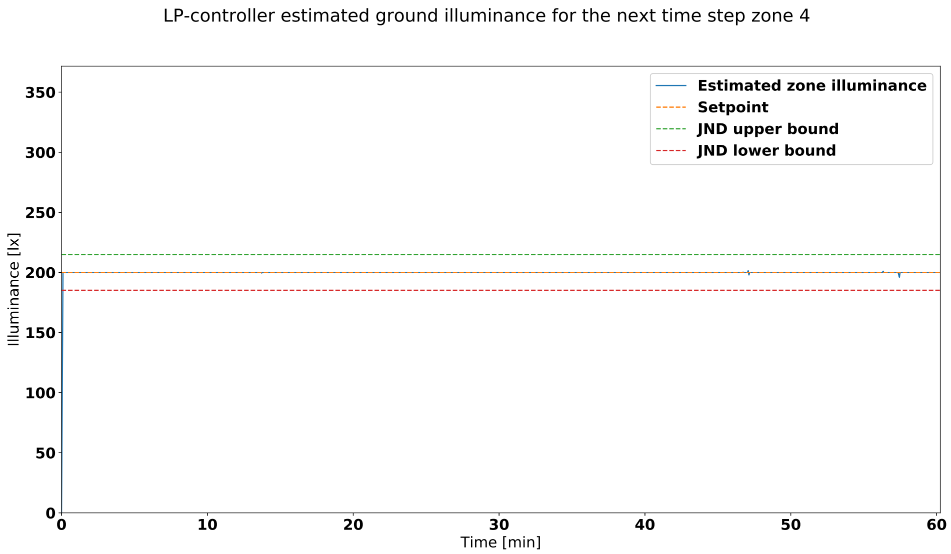
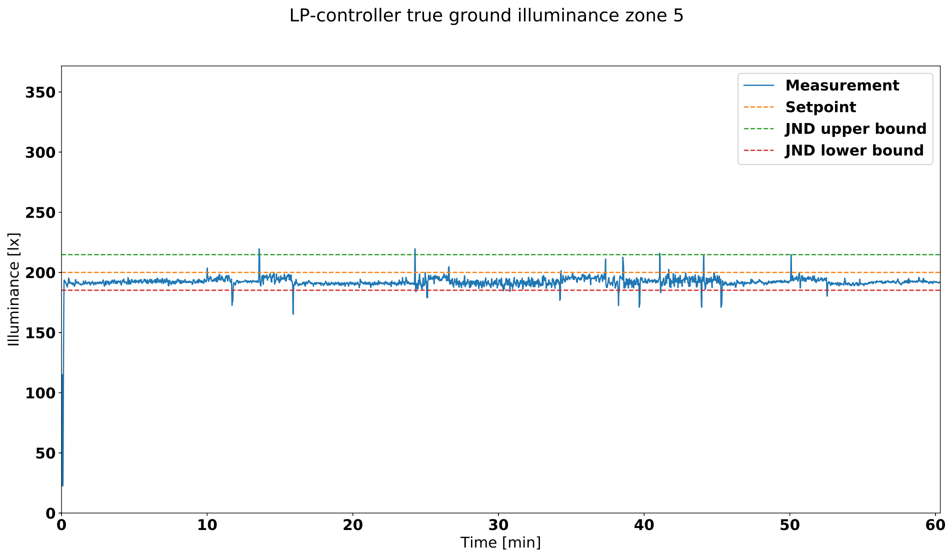


Figure A.28: Zone 4



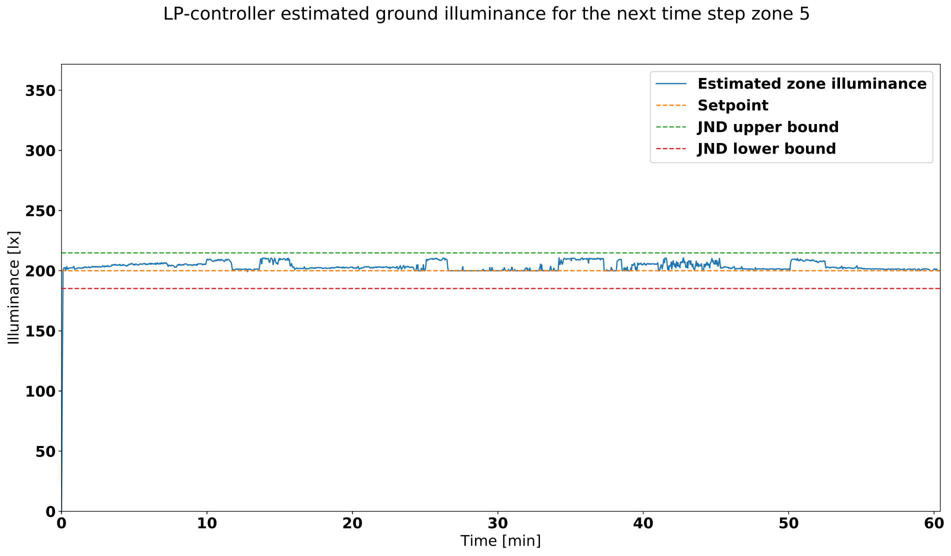
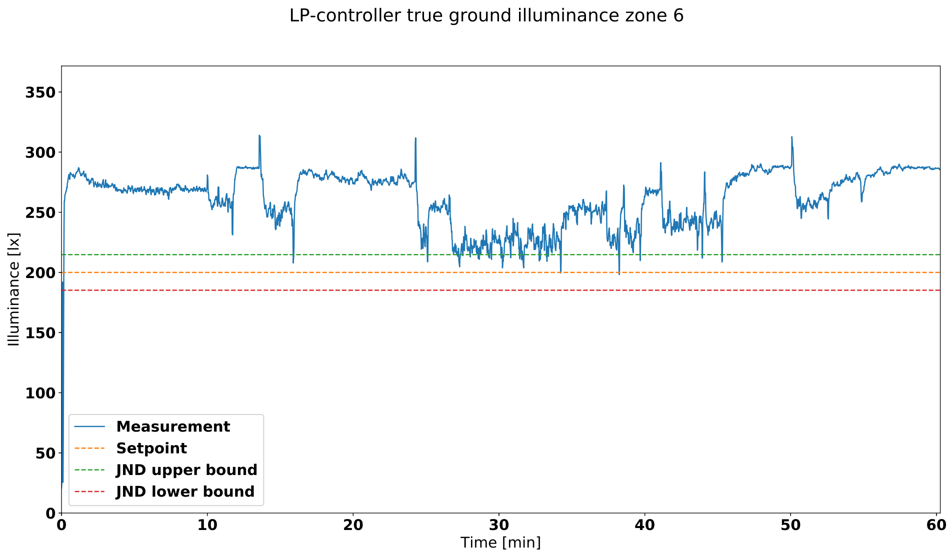


Figure A.29: Zone 5



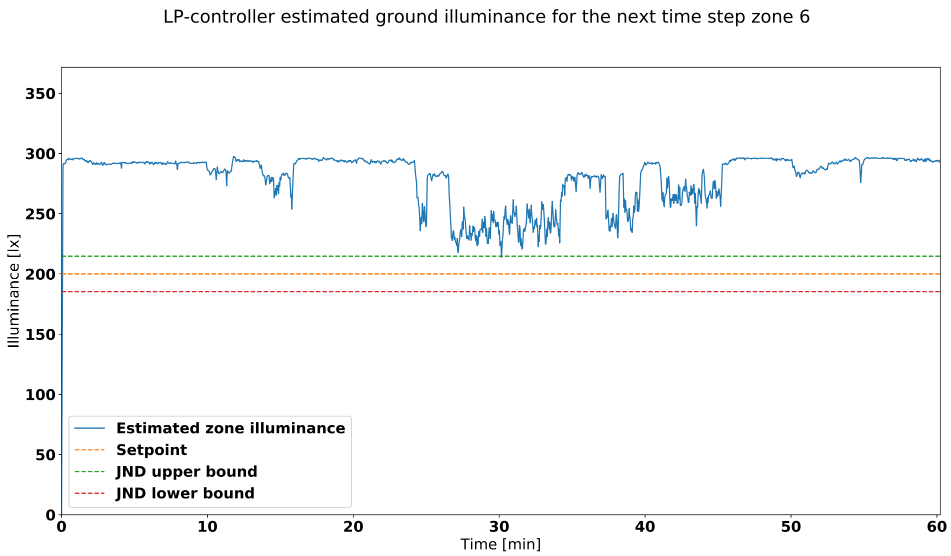
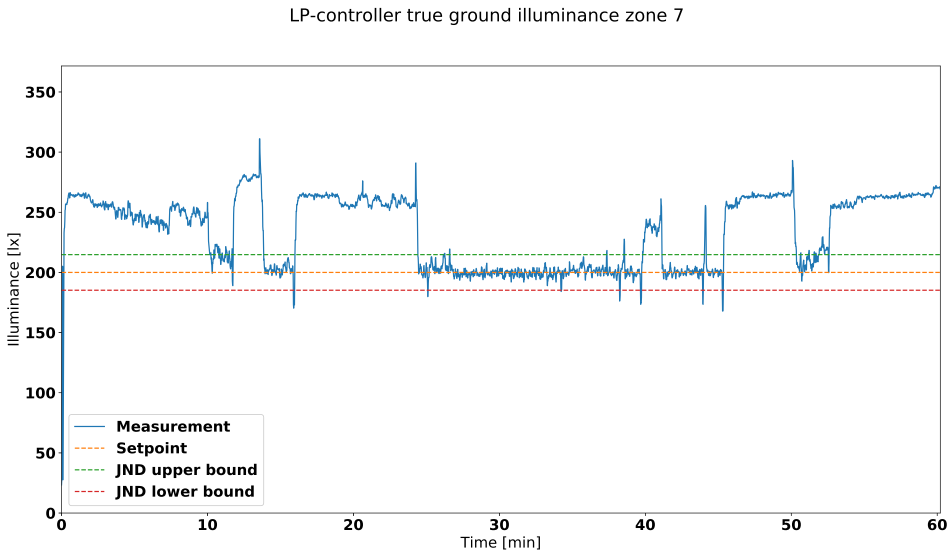


Figure A.30: Zone 6



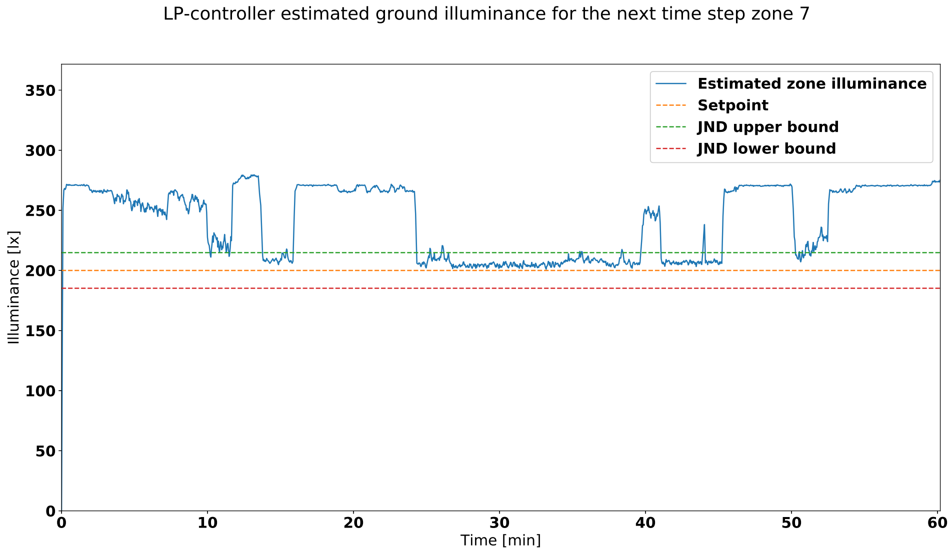
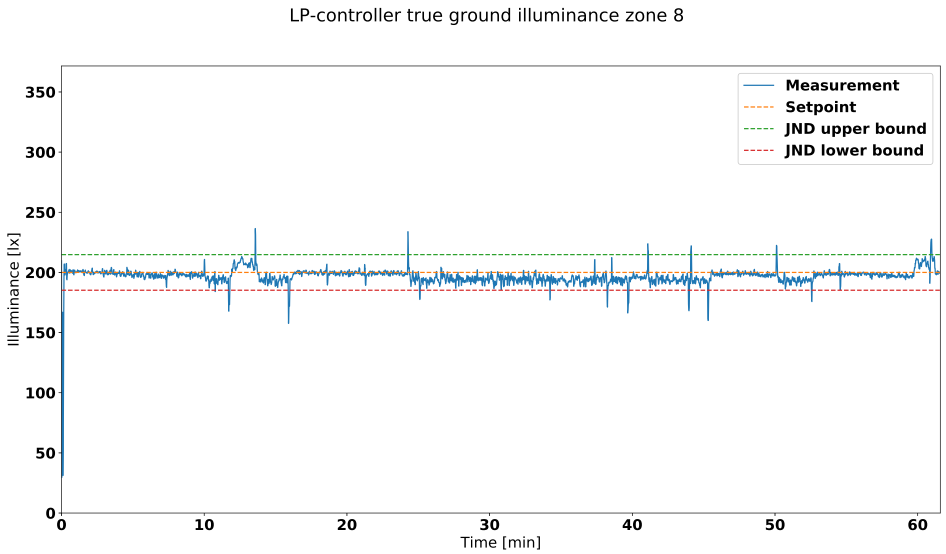


Figure A.31: Zone 7



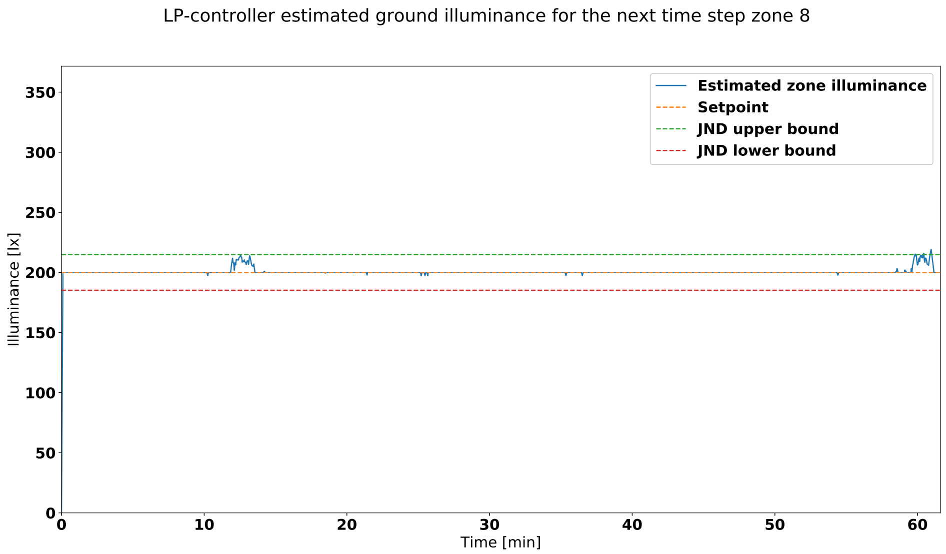


Figure A.32: Zone 8

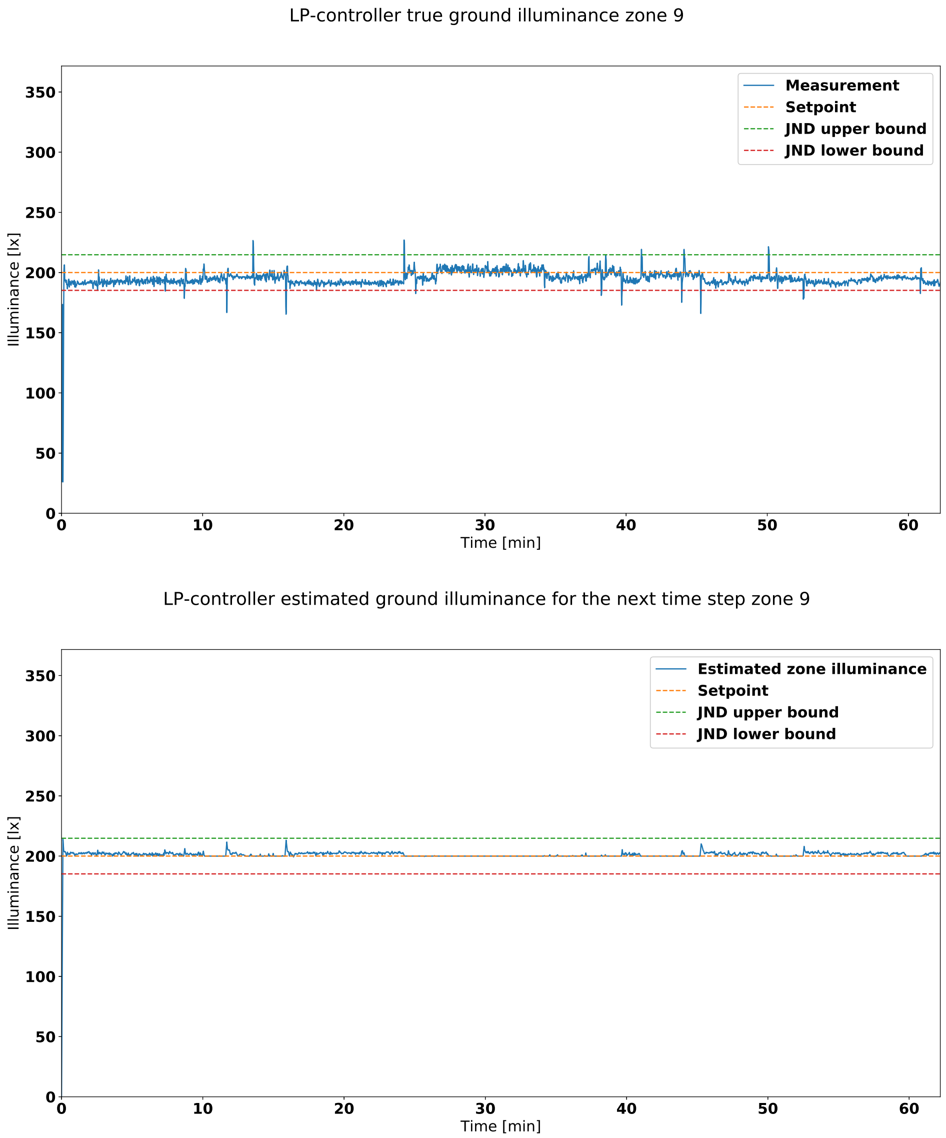
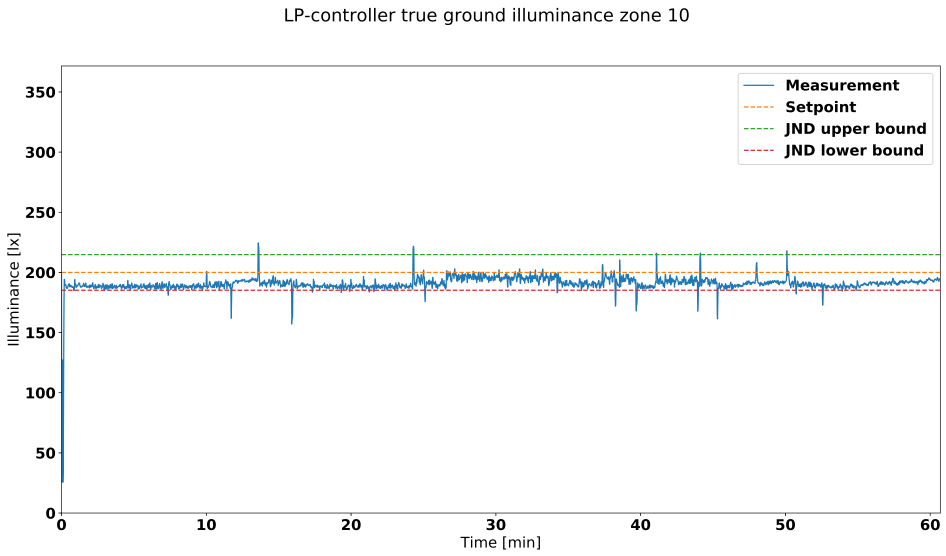


Figure A.33: Zone 9



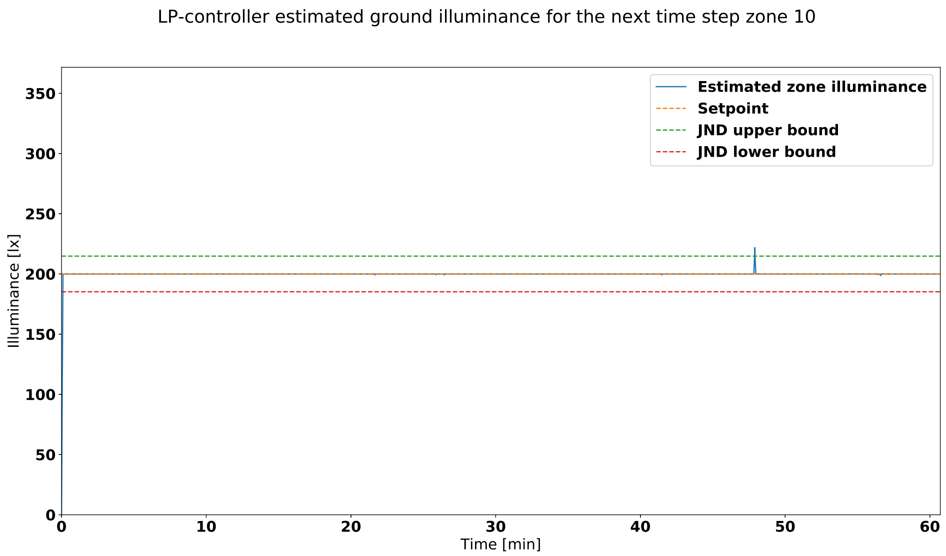
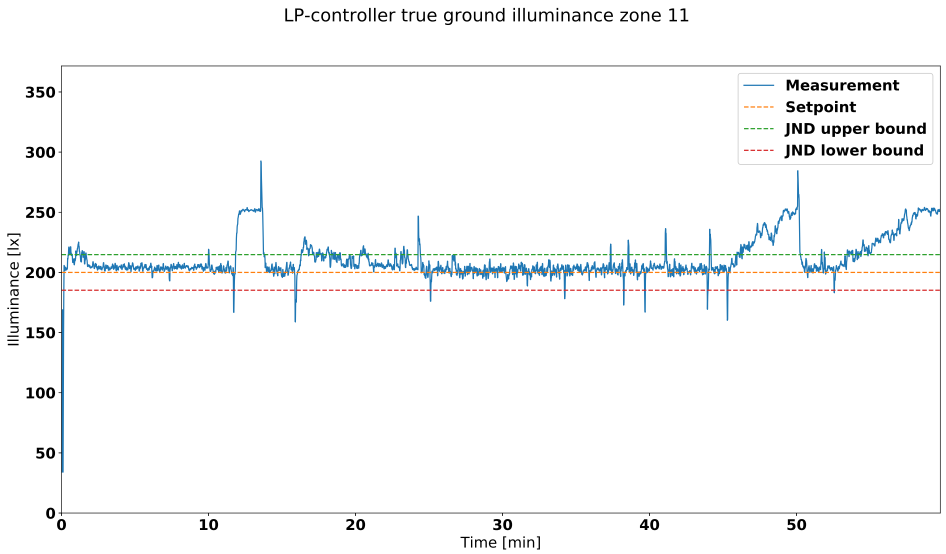


Figure A.34: Zone 10



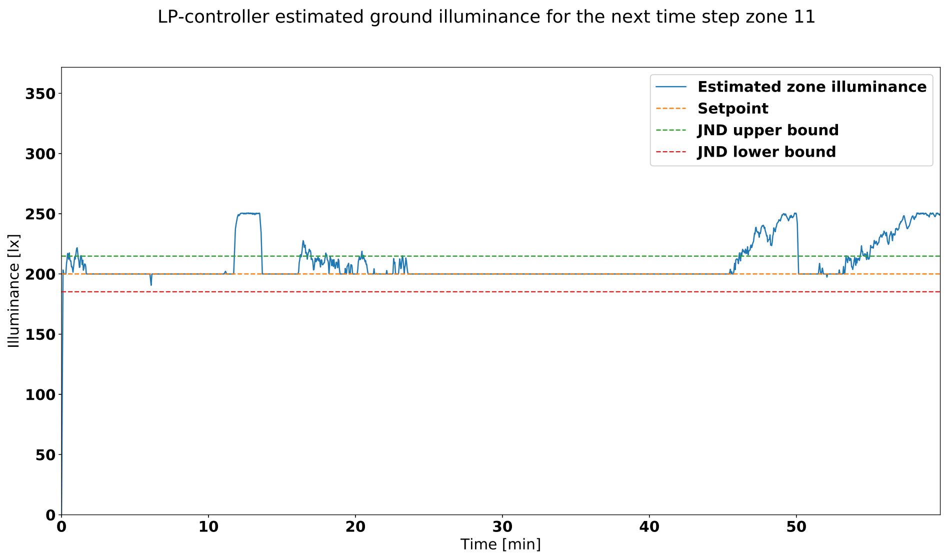
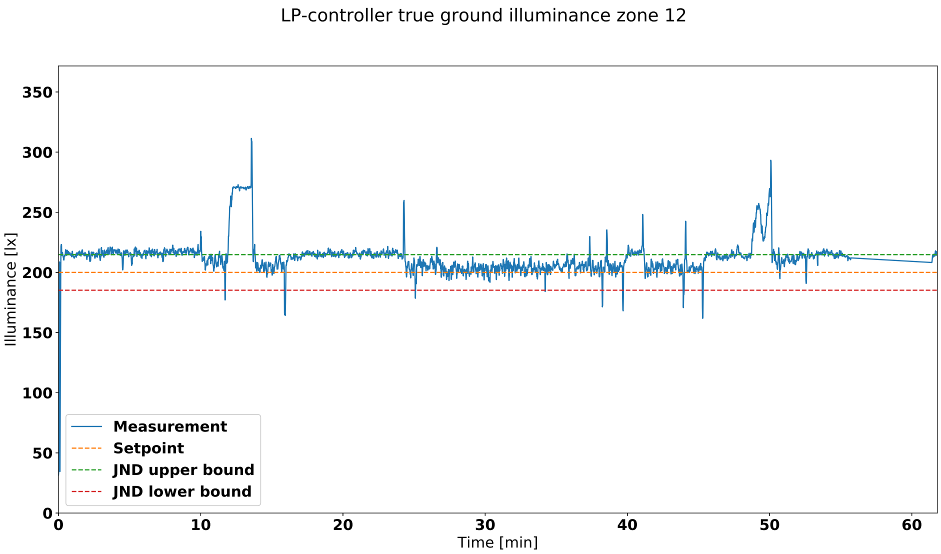


Figure A.35: Zone 11



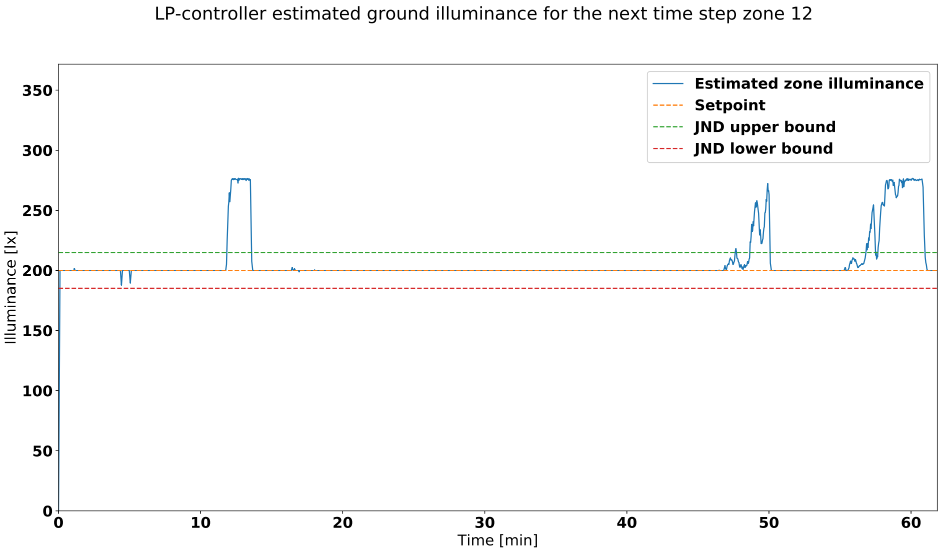


Figure A.36: Zone 12

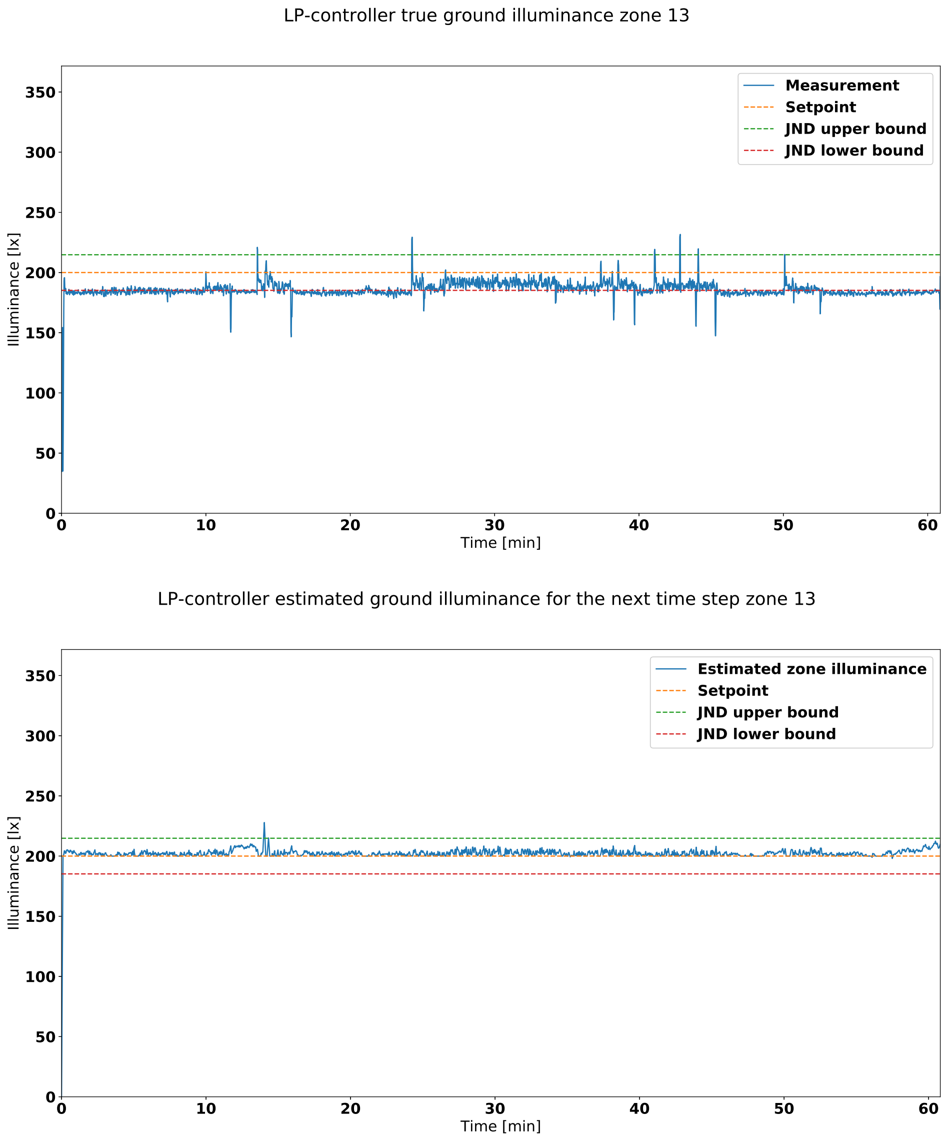


Figure A.37: Zone 13

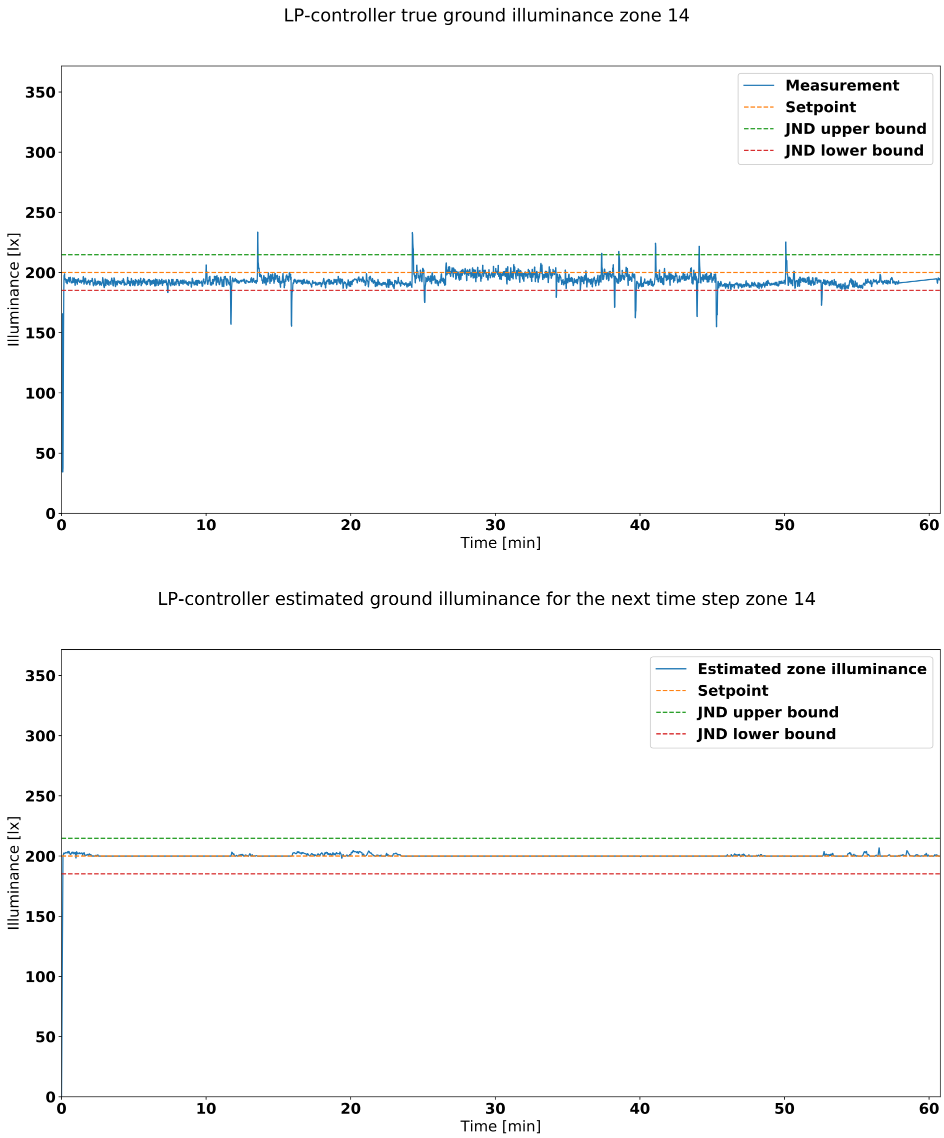
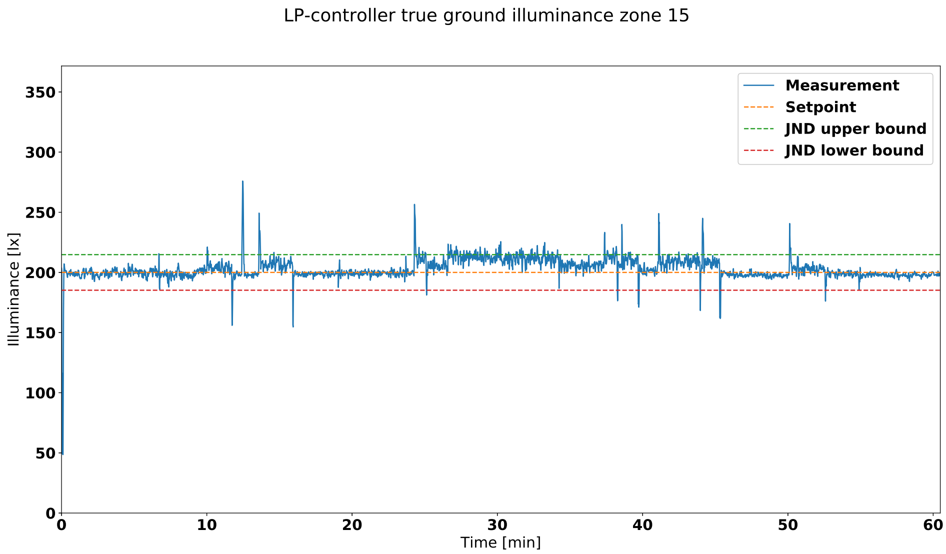


Figure A.38: Zone 14



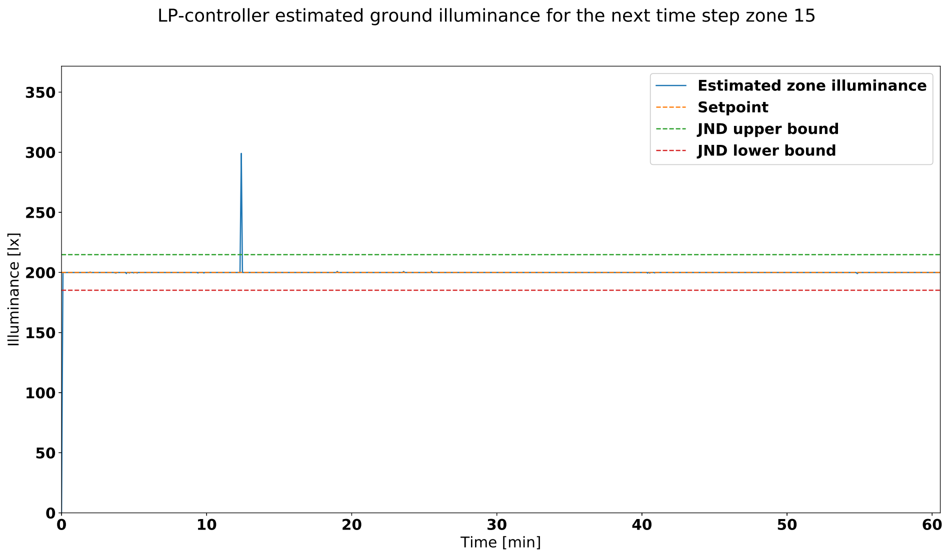
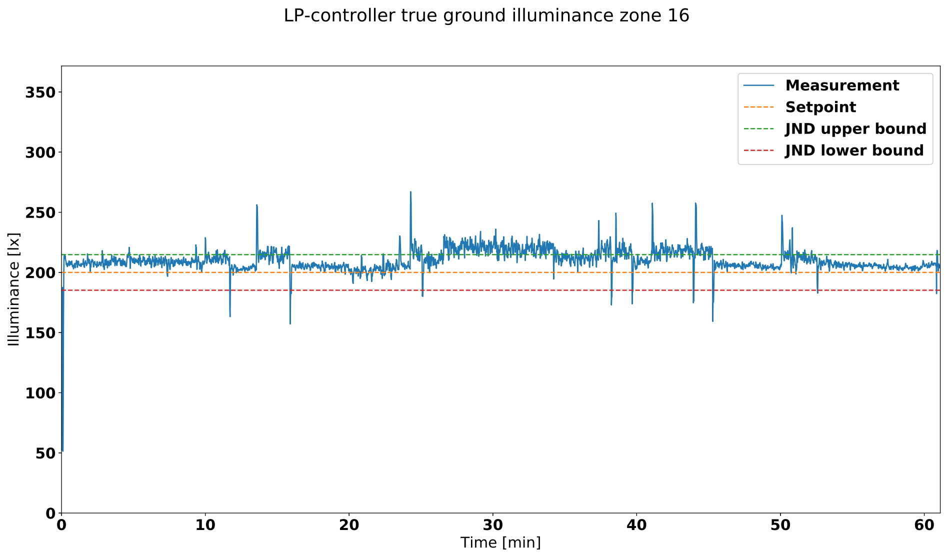


Figure A.39: Zone 15



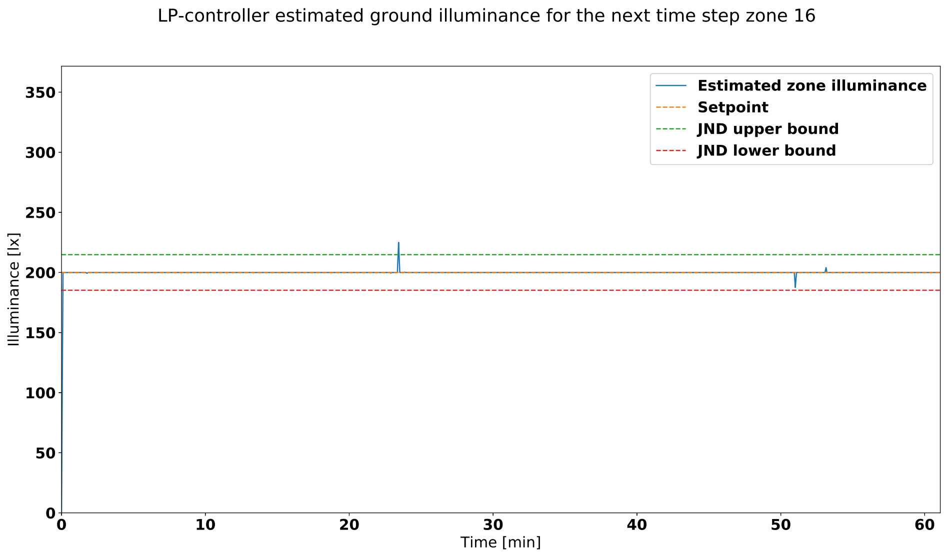


Figure A.40: Zone 16

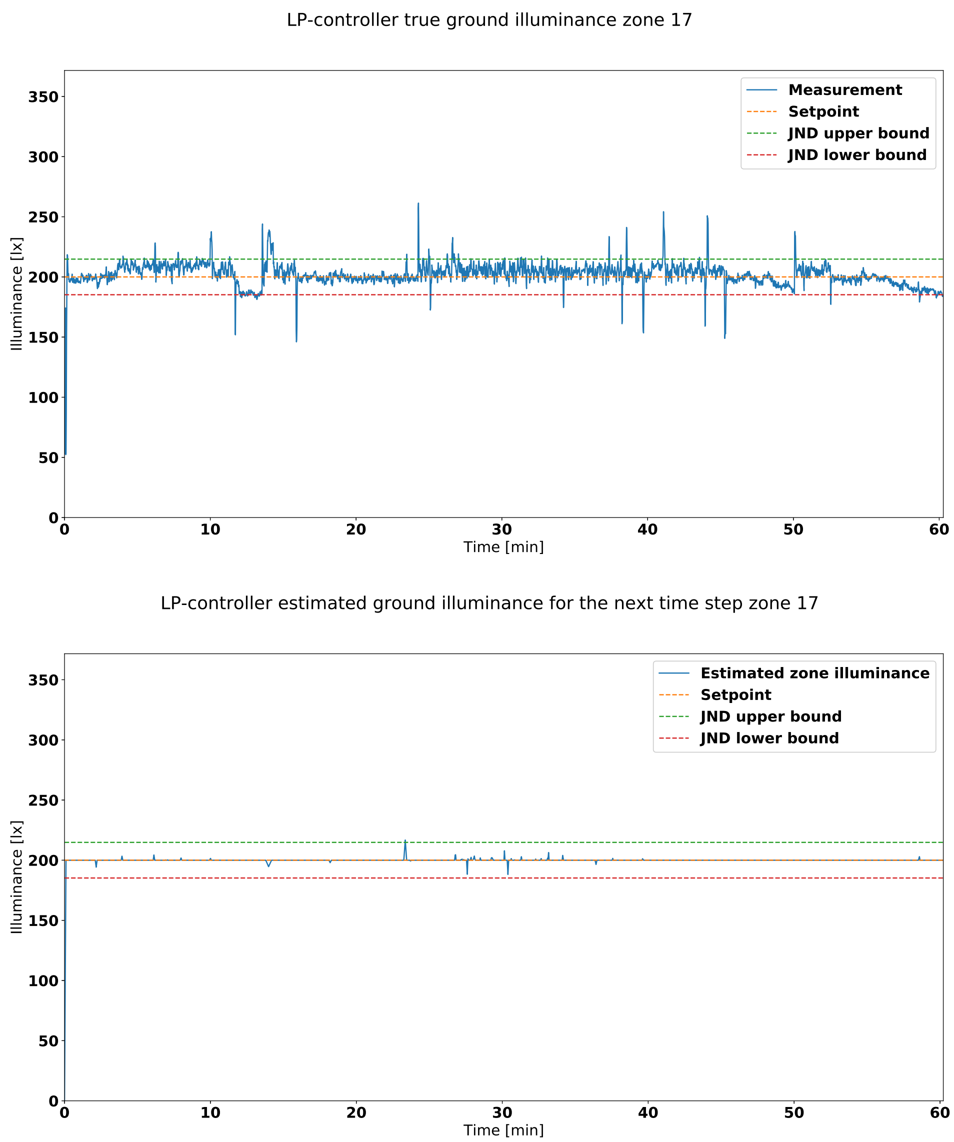


Figure A.41: Zone 17

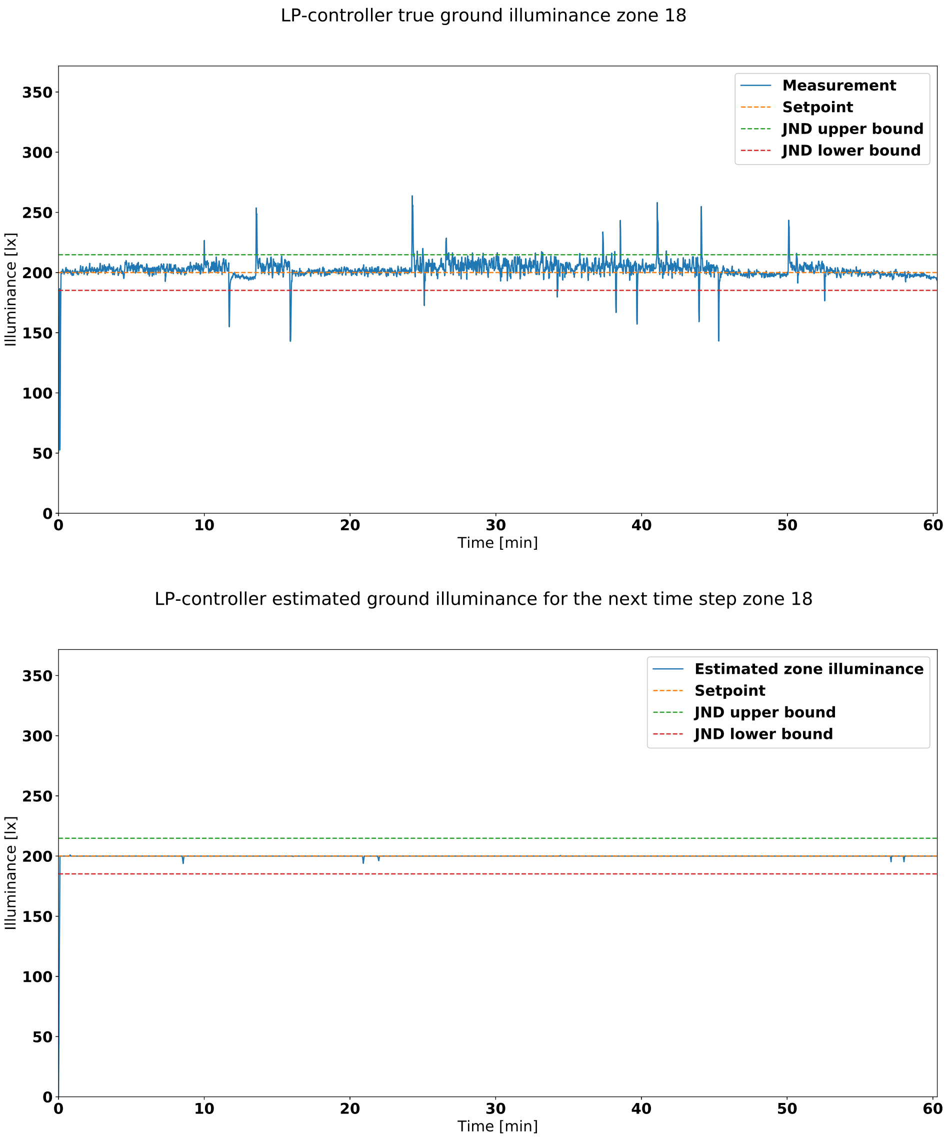


Figure A.42: Zone 18

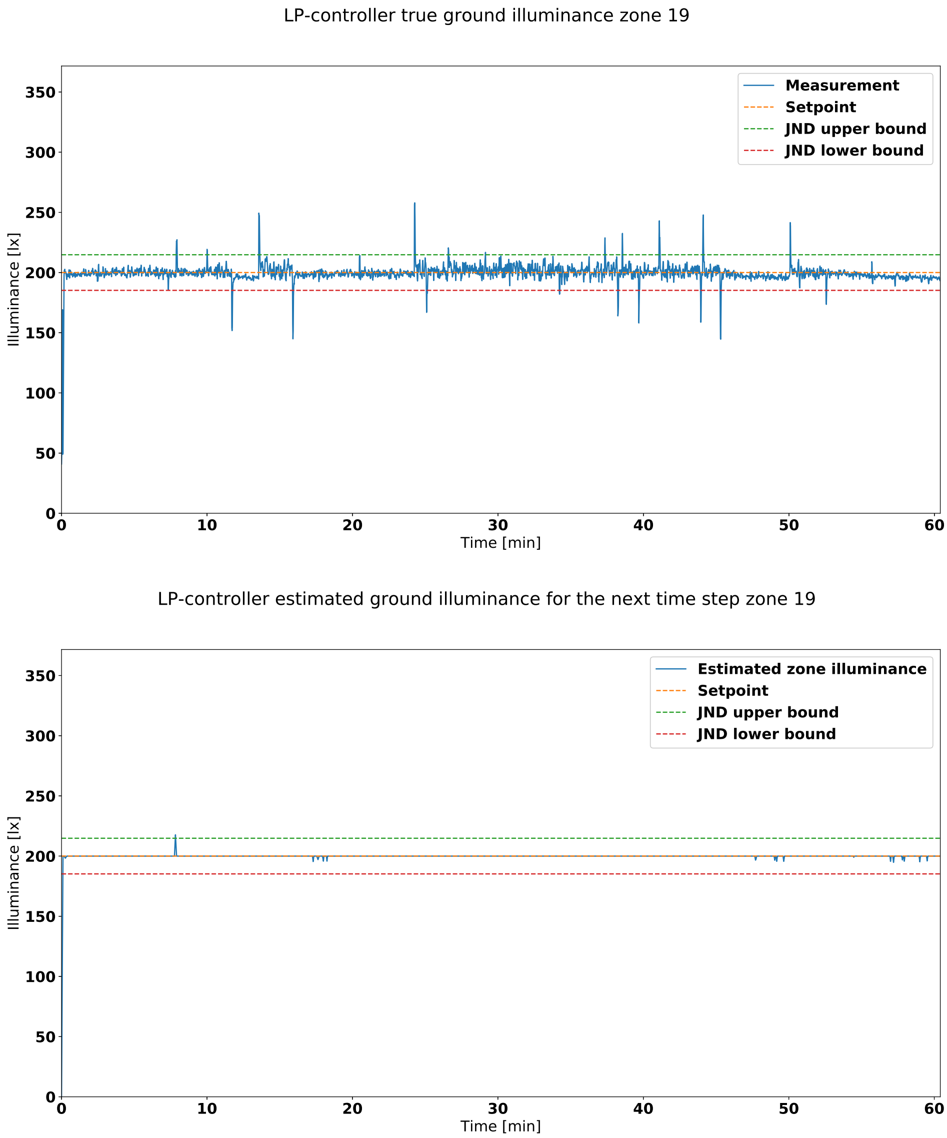
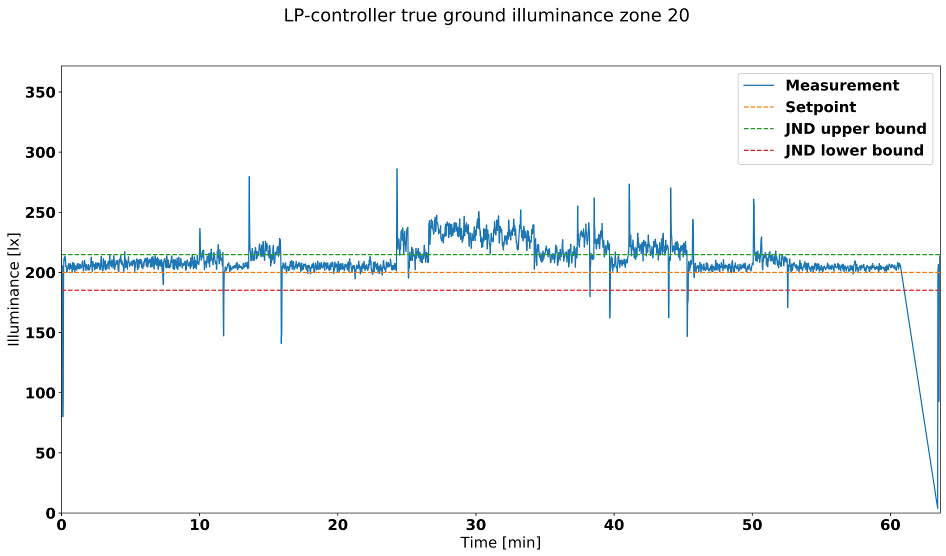


Figure A.43: Zone 19



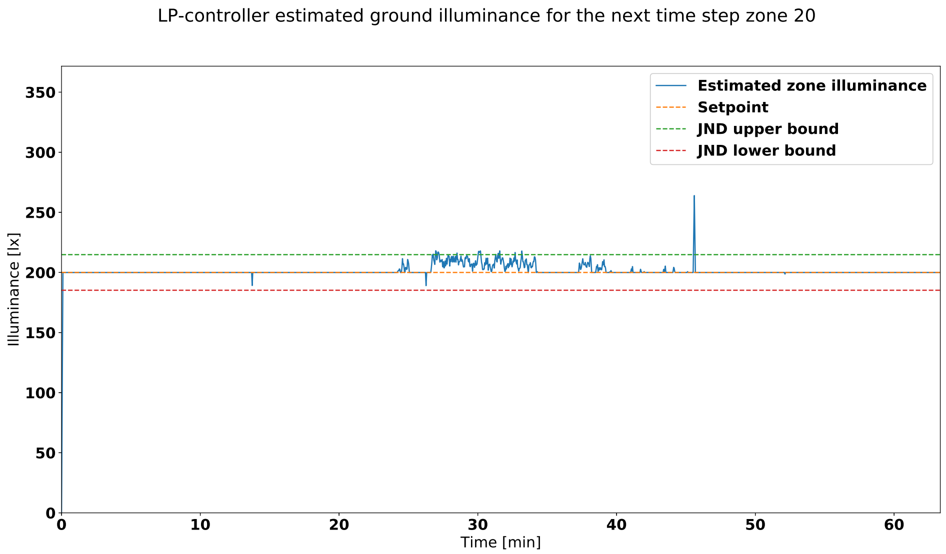
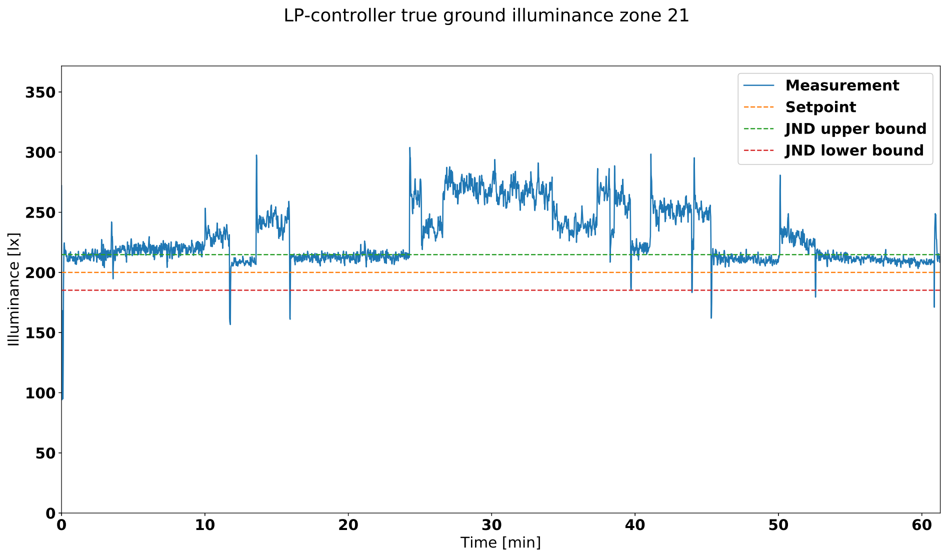


Figure A.44: Zone 20



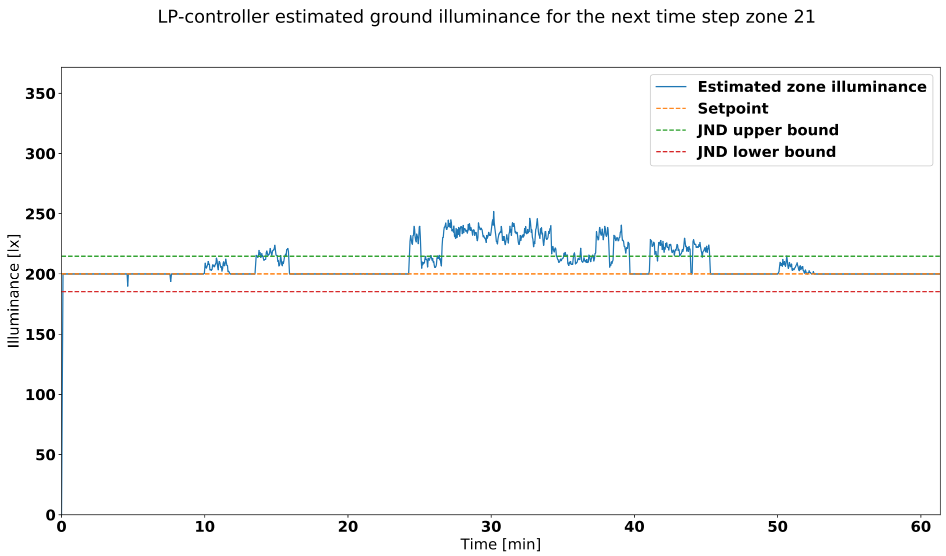
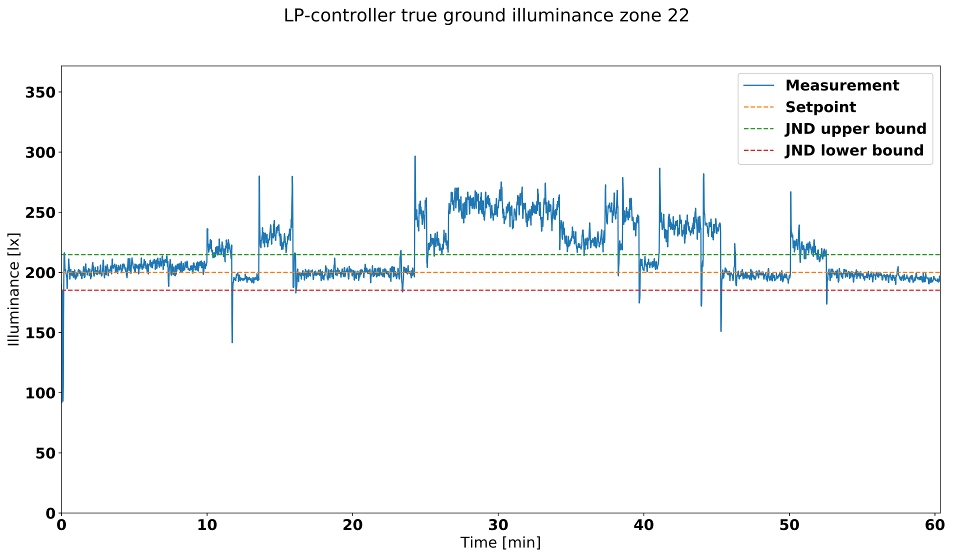


Figure A.45: Zone 21



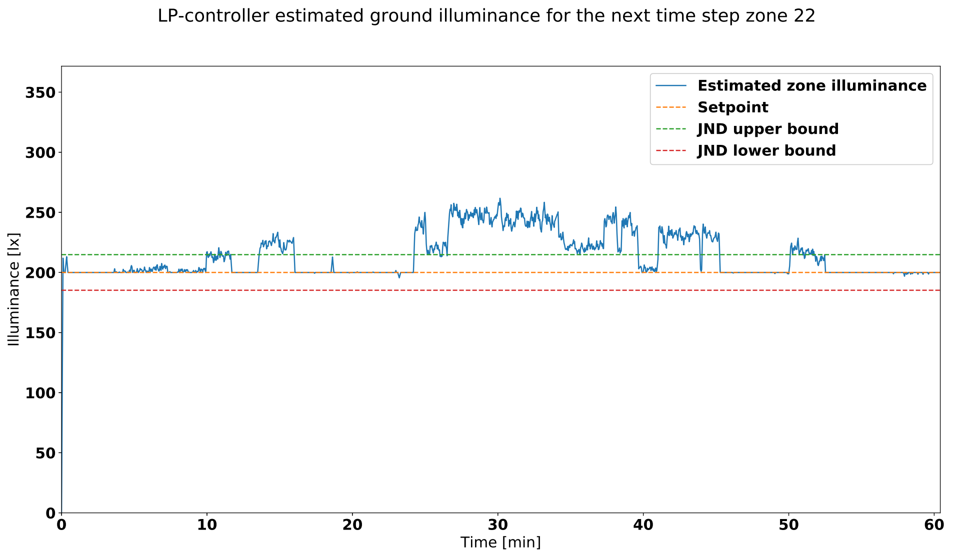


Figure A.46: Zone 22

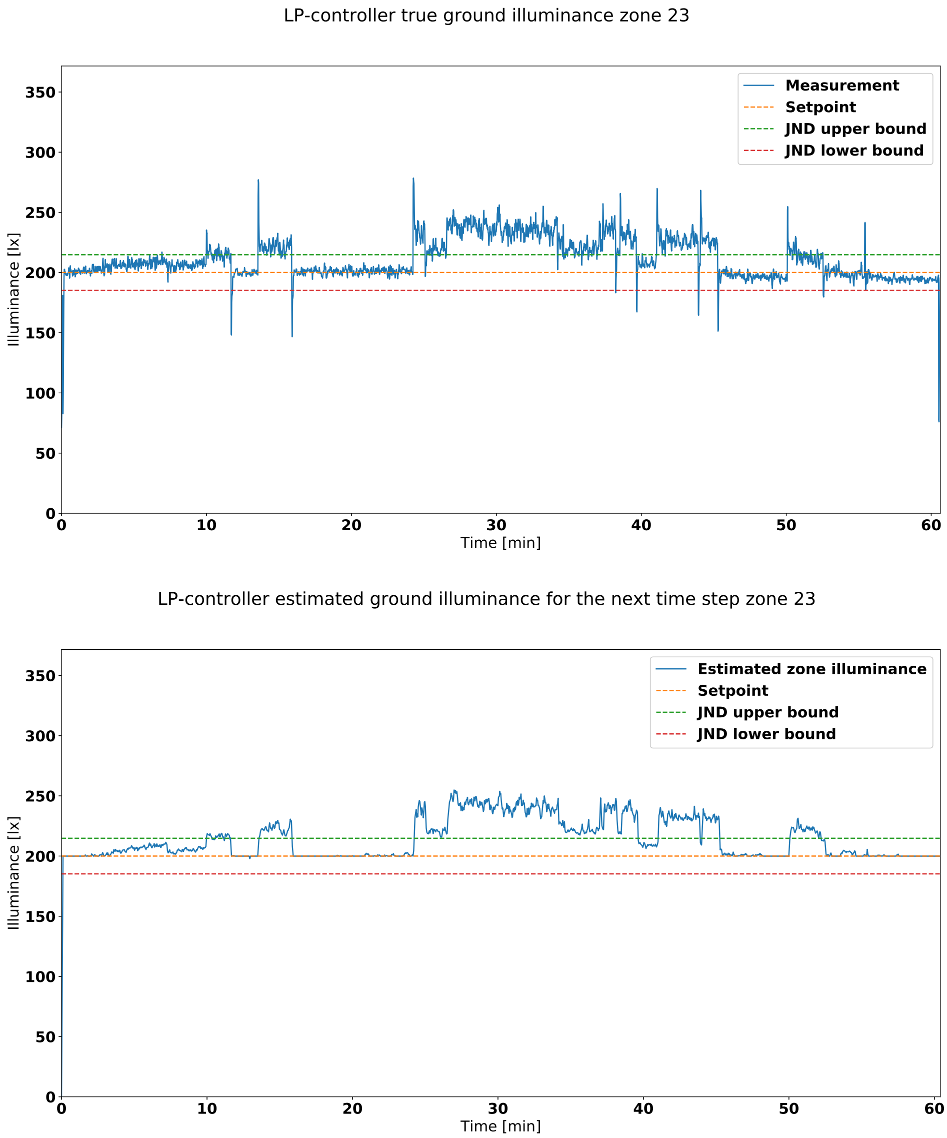


Figure A.47: Zone 23

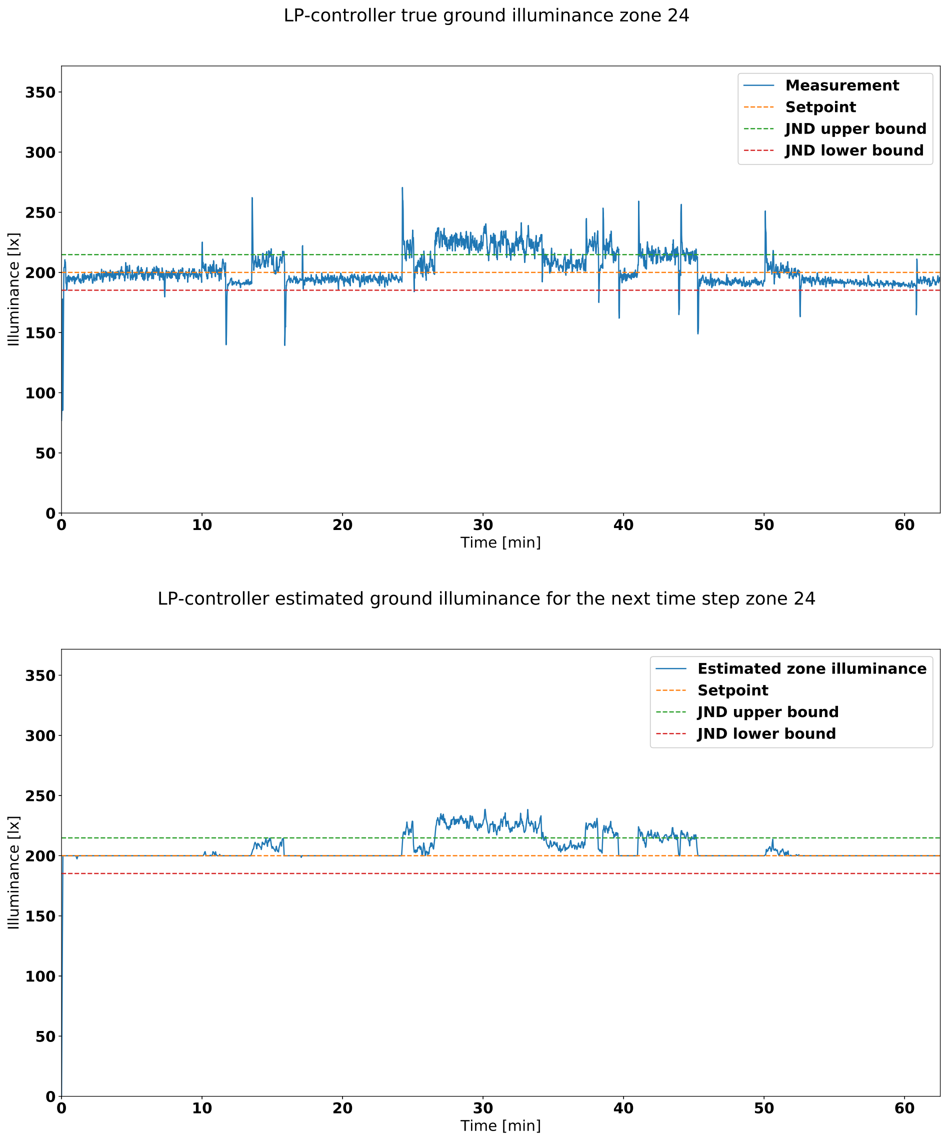


Figure A.48: Zone 24