

# Personal lighting control with occupancy and daylight adaptation



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*To whom has always been with me ...*



## **Abstract**

Personal control with occupancy and daylight adaptation is considered in a lighting system with multiple luminaires. Each luminaire is equipped with a co-located occupancy sensor and light sensor that respectively provide local occupancy and illumination information to a central controller. Users may also provide control inputs to indicate a desired illuminance value. Using sensor feedback and user input, the central controller determines dimming values of the luminaires using an optimization framework. The cost function consists of a weighted sum of illumination errors at light sensors and the power consumption of the system. The optimum dimming values are determined by solving an unconstrained optimization and a constrained optimization. The constrained solution is solved with the constraints that the illuminance value at the light sensors are above the reference set-point at the light sensors and the dimming levels are within physical allowable limits. Different approaches to determine the set-points at light sensors associated with multiple user illumination requests are considered. The performance of the proposed controllers is compared with a reference stand-alone controller under different simulation scenarios in an open-plan office lighting system.



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# Chapter 1

## Introduction

This thesis was written based on an intern-ship project developed from July 2014 till April 2015 in *Philips Research & Development*, High Tech Campus, Eindhoven, The Netherlands. The department was formerly called Lighting Control Systems, now renamed as Smart Professional Spaces. The entire work has been done under the supervision of Senior Scientist Ashish Pandharipande and Ph.D. David Caicedo. This work resulted in two external publications:

- INDIN 2015 IEEE International Conference on Industrial Informatics [25] (published),
- Energy and Buildings, an international journal devoted to investigations of energy use and efficiency in buildings [26] (in review).

Royal Philips is a diversified health and well-being company, focused on improving people's lives through meaningful innovation in the areas of Healthcare, Consumer Lifestyle and Lighting. Headquartered in the Netherlands, Philips posted 2013 sales of EUR 23.3 billion and employs approximately 115,000 employees with sales and services in more than 100 countries.

The company is a world leader in cardiac care, acute care and home healthcare, energy efficient lighting solutions and new lighting applications, as well as male shaving, grooming and oral healthcare [27]. Philips Lighting is a global market leader with recognized expertise in the development, manufacturing and application of innovative lighting solutions. Philips has pioneered many of the key breakthroughs in lighting over the past 123 years, laying the basis for the current strength and ensuring

that the company is well-placed to be a leader in the digital transformation. The aim is to further strengthen the position in the digital market through added investment in Light Emitting Diode (LED) leadership while at the same time capitalizing its broad portfolio, distribution and brand in conventional lighting. Philips addresses people's lighting needs across a full range of market segments. Indoors, they offer lighting solutions for homes, shops, offices, schools, hotels, factories and hospitals. Outdoors, they offer solutions for roads (street lighting and car lights) and for public spaces, residential areas and sports arenas. In addition, Philips addresses the desire for light-inspired experiences through architectural projects. Finally, it offers specific applications of lighting in specialized areas, such as horticulture and water purification.

Philips Lighting spans the entire lighting value chain - from light sources, luminaires, electronics and controls to full applications and solutions - through the following businesses:

- Light Sources & Electronics,
- Consumer Luminaires,
- Professional Lighting Solutions,
- Automotive Lighting,
- Lumileds.

The Department of Philips Research & Development is located in High Tech Campus, Eindhoven, The Netherlands. High Tech Campus Eindhoven is the smartest km<sup>2</sup> in The Netherlands with more than 125 companies and institutes, and approximately 10.000 researchers, developers and entrepreneurs working on developing future technologies and products. The Campus helps to accelerate innovation by offering easy access to high tech facilities and international networks. Campus companies, such as Philips, NXP, IBM, Intel, strategically decide what knowledge, skills and R& D facilities they share in order to achieve faster, better and more customer-oriented innovation in the application fields Health, Energy and Smart Environments. Located at the heart of Brainport these companies are responsible for nearly 40% of all Dutch patent applications [28].

## 1.1 Philips' lighting commercial products

Philips became worldwide famous thanks to its lighting bulbs. Nowadays, the products are much wider and evolved in many different fields, but still lighting applications are of interest. Tradition and innovation mix in the LED lights among Philips' products: they provide a soft white light, energy savings, a higher quality of light and they are dimmable. Philips has a wide range of dimmable LED products, making it easy to adjust the light intensity. LED dimming technologies are the ideal replacement for incandescent and halogen solutions, in terms of performance, compatibility and light output. Philips LED bulbs are able to create the same deep, warm tones as a dimmed incandescent. Lighting is an unobtrusive, yet very practical way to enhance the atmosphere in your home. LEDs are able to provide a wide range of white colors, each one linked to a color temperature; this temperature is measured in Kelvin (K). A low color temperature creates a warm, cosy light effect, while a high color temperature creates a cool, more energizing effect. The majority of Philips LED lighting products provides from 2200 Kelvin, which is soft white light, to 6500 Kelvin, which is a cool white light.

In order to understand the energy use of a light source, lumens and wattage are important concepts. In simple words, a LED light uses far less energy (watts) to produce the same light output (lumens). An example: a LED bulb uses only 10.5 watts to produce a light output of 800 lumens, while a traditional light bulb uses 60 watts (6 times more energy) to generate the same lumen output. Thus LED lighting is very energy efficient compared to traditional lights, because it uses less energy to produce the same light output. LED lights approximately save up to 85% energy. Moreover, the lifetime of a LED bulb or fixture is up to 20 times longer with respect to a traditional bulb, avoiding the hassle of frequent changing of light bulbs. To provide a quantitative idea consider that a traditional incandescent light bulb has a lifetime of about 1000 hours, while Philips LED lighting has a lifetime up to 25000 hours, which is more than 22 years. There are thus two things that make LED lighting the most energy efficient solution: very low energy usage and a very long lifetime. This significantly reduces waste of energy and also saves money in the long term.

## 1.2 Buildings and lighting systems nowadays

The major portion of electrical energy consumption in commercial buildings is due to lighting for office spaces. According to several researches buildings consume a great part of the total available energy, one-third of those is utilized for lighting needs [1], [33]. One of the next years' goals is to achieve important energy savings. Even though many systems in real world are becoming smart, artificial intelligence has not been significantly applied to lighting systems, which are essential in everyday life. Energy consumption may be reduced by using appropriate lighting control techniques, especially combining these techniques with LED luminaires. It has been proved [11], [8] that it is possible to achieve 40% or 50% of energy savings with an intelligent lighting control system with respect to a standard system constituted only by with on/off switches.

The aim of this research field is to reduce energy consumption while still keeping high level of users' satisfaction. These goals are clearly conflicting, so a trade-off must be reached: an intelligent lighting control system must manage energy savings and occupants' preferences. Thus the control of artificial lighting has recently received significant attention, in particular by adapting to occupancy and daylight changes over time and space [2]-[11]. The adoption of LED luminaires has made such control easy since it is possible to accurately dim each luminaire individually taking into account local presence and light sensing inputs. While saving energy is an important objective, controller design must also take personal illumination needs of users into account. In fact, studies have shown that users may require differing levels of illumination and a lighting system that caters to these needs can enhance user satisfaction and productivity [12], [13], [14]. Nowadays with the advent of smart-phone and tablet such type of request became more feasible since the interaction between occupants and luminaires may be simplified by some user-friendly applications.

## 1.3 Lux: illuminance unit of measure

In this thesis the concept of lux will be often used. The lux the SI unit of illuminance and luminous emittance measuring luminous flux per unit area. It is equal to one lumen per square meter. In photometry, this is used as a measure of the intensity, as perceived by the human eye, of light that hits or passes through a surface. A given



amount of light will illuminate a surface more dimly if it is spread over a larger area, so illuminance (lux) is inversely proportional to area when the luminous flux (lumens) is held constant [30]. In table 1.1 some examples of the illuminance provided under various conditions are shown:

<b>Illuminance</b>	<b>Surface illuminated by:</b>
0.0001 lux	Moonless, overcast night sky (starlight)
0.002 lux	Moonless clear night sky with airglow
0.27–1.0 lux	Full moon on a clear night
3.4 lux	Dark limit of civil twilight under a clear sky
80 lux	Office building hallway lighting
100 lux	Very dark overcast day
320–500 lux	Office lighting
1000 lux	Typical TV studio lighting
10000–25000 lux	Full daylight, not direct sun
32000–100000 lux	Direct sunlight

Table 1.1 Examples of illuminance values under various conditions.

## 1.4 Contribution

In this work, a lighting system with multiple LED luminaires and a central controller is considered. Each luminaire has a co-located occupancy sensor and a light sensor. These sensors respectively provide binary occupancy and the net illuminance level within their field-of-view. Additionally, users may request for a desired illuminance levels in their zone. A zone is a logical partitioning of the physical horizontal workspace plane, for instance it can be defined by a region around a work desk. The sensing values and user requests are sent to a central controller, where a designed control law is used. The dimming values, or dimming level, are evaluated by the controller and sent back to the corresponding luminaires. The control law has to be designed such that the total artificial light output contribution, in combination with daylight contribution, results in net illuminance above desired levels at the workspace plane. Let  $W_o$  and  $W_u$  denote the average illuminance values desired at the workspace plane in an occupied and unoccupied zone respectively.  $W_o$  and  $W_u$  are measured in lux.

Two lighting control scenarios are considered in this thesis. In the first scenario, lighting control is based solely on pre-specified illumination targets in occupied and unoccupied zones and control feedback is from the occupancy and light sensors. In the second scenario, lighting control is based additionally on user control requests. In this scenario, we consider different approaches to specify the set-points of light sensors that are associated with multiple user requests.

The illuminance targets at the workspace plane are specified in terms of sensor set-points at corresponding light sensors co-located at the ceiling luminaires. These set points are determined in a night-time calibration step. In the absence of daylight, the luminaires are turned to maximum intensity and the average workspace illuminance value along with the light sensor measurements are stored. The light sensor set-points corresponding to a specific desired average illuminance are then obtained by suitable linear scaling.

The lighting control problem is posed using an optimization framework. The optimum dimming values are obtained by minimizing a cost function that is a weighted sum of a component related to the illumination errors at the light sensors and another component related to the power consumption of the lighting system. This cost function is minimized using two different approaches:

- an unconstrained optimization,
- a constrained optimization.

From the first approach it is possible to derive explicitly the form of the optimal control vector. Instead the constrained optimization is under the constraints that the illuminance value attained at the light sensors is no smaller than the reference set-points and that the dimming levels of the luminaires take values within physical limits. This constrained multi-variable minimization problem is then solved using convex optimization techniques.

The performance of the proposed control algorithms are evaluated with simulations on an illustrative open-plan office. Using the stand-alone controller designed in [11] as benchmark, it will be shown that the proposed constrained approach provides better performance in terms of under-illuminance, overshoot, settling time and achieving the reference set-points.

## 1.5 Lighting control systems' state of art

Different lighting control approaches exist in literature, depending on the system architecture, connectivity and optimization algorithms employed. Various optimization based frameworks have been proposed in literature for daylight and occupancy adaptation [2], [3], [4], [16], [17]. A numerical optimization approach to energy-efficient central control of polychromatic solid state lighting systems was presented in [31]. Under a centralized control system, a simplex algorithm was used in [16] to solve the resulting optimization problem for achieving illumination rendering adapted to occupancy, with [17] extending the control system to take spatio-temporal daylight variations into account. In these works, knowledge of the light distribution at the workspace plane was assumed; the performance reported as such can be seen as theoretical performance limits.

Two networked lighting systems were taken into account in [4] and [5] by considering the light sensors at work desks. In particular in [5] the authors proposed a distributed lighting system equipped with a controller which was able to control luminaires in a neighbourhood using infra-red communication. Measurements of light sensors in a desk-placed or portable configuration can however be sensitive to environmental changes such as occupant movements and shadowing of objects, thus affecting illumination performance of the lighting system. It is thus common practice to install the light sensors at the ceiling [8], [11], [18], [19]. In this case, since light measurements are on a plane different from the one where the spatial illumination rendering is of interest, a calibration step is required to map the measurements across the ceiling and workspace planes. Moreover stand-alone as well as networked controllers for distributed lighting systems were considered in [11], under the assumption of perfect communication channel. Herein, a stand-alone controller with offset was considered. The positive offset in the control law was introduced to deal with the problem of under-illumination that occurs due to different contributions of daylight over the workspace and light sensors over time. This observation was made early in [19] and in [32], for a single light sensor-driven lighting system.

## 1.6 Thesis structure

The remainder of the thesis is organized as follows.

In Chapter 2 an analytical model of the lighting system under consideration is presented. In Chapter 3, it is first explained how the light sensor set-points are chosen. Secondly, the reference stand-alone controller designed in [11] is presented and it shall be used as a benchmark. This chapter is then concluded explaining the two proposed optimization methods: the unconstrained approach and the constrained approach. The performance of the proposed controllers is then evaluated and compared with the stand-alone controller using an open-plan office model and results are discussed in Chapter 4. Finally, in Chapter 5 conclusions are drawn.

# Chapter 2

## System model

The lighting system studied in this thesis is located in a office-type room. The system to be controlled is composed by several luminaires placed at the ceiling and equipped with sensors. An illustrative open-plan office area is depicted in Figure 2.1. The control aim is to reach a desired illuminance at the workspace plan, so where people are working. Each luminaire has an occupancy sensor and a light sensor. The occupancy sensor detects whether there is local unoccupancy or occupancy within its field-of-view, and then provides a binary value, 0 or 1 respectively. The illuminance measurement at the light sensor corresponds to the net amount of light (daylight contribution and artificial light from the luminaires) reflected back within its field-of-view from various objects. These sensor measurements are sent periodically to the controller. The sensor feedback period is chosen such that the controller reacts with sufficient speed to daylight changes, while not overloading the communication bandwidth; practical choice for the period is in the order of seconds. In this work we shall assume high bandwidth communication; communication is thus assumed to be reliable and message losses and delays are ignored. Moreover, users may request desired illuminance values over his/her occupied zone and such information is also available to the controller.

The luminaires considered are composed by LEDs. These types of luminaires allow to set the illuminance at a specific and desired dimming level, differently from the traditional luminaires which can be switched on or off only. In this work this level can take a real value between 0 and 1 to satisfy the physical limits of the luminaires. Moreover LED luminaires permit to model the lighting system as a linear model. As

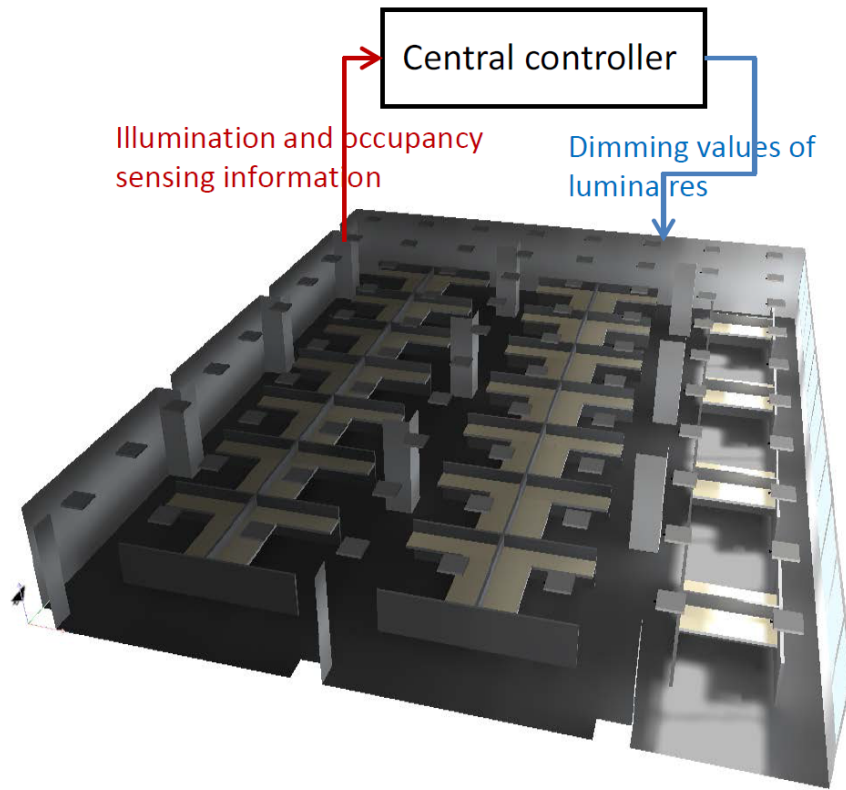


Fig. 2.1 Lighting control system with multiple luminaires and co-located sensors in communication with a central controller.

shown in [8] and depicted in Figure 2.2 if the measured illuminance value is taken as the output and the dimming level as the input, the function is well approximated by a linear model. In figure 2.2 denote  $\hat{E}_{m,n}(d_n)$  to be the measured illuminance at the  $m$ -th light sensor when the  $n$ -th luminaire is at dimming level  $d_n$ , in the absence of daylight and when the other luminaires are turned off.

Hereon, it shall be considered the following closed-loop system (Figure 2.3):

- the light sensors read the illuminance at the ceiling providing a feedback to the controller,
- the presence sensors send the binary value to the controller, so that it knows if a zone is occupied or unoccupied,
- the controller knows the reference set-points so it can compute the error and then a dimming level according to a specific control law,

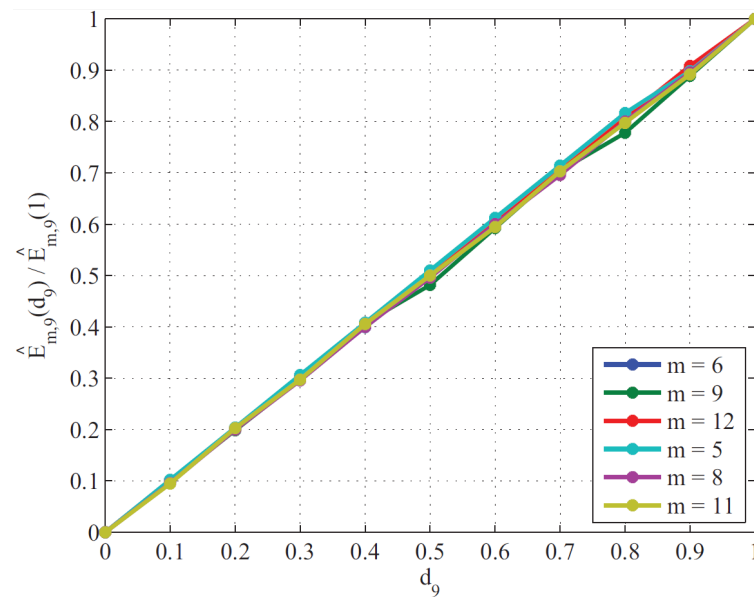


Fig. 2.2 Linearity of illuminance values at light sensor  $m$  with respect to the dimming level of luminaire 9, for  $m = 6, 9, 12, 5, 8, 11$  (image taken from [8]).

- once the dimming level is computed the controller sends it back to the corresponding luminaire.

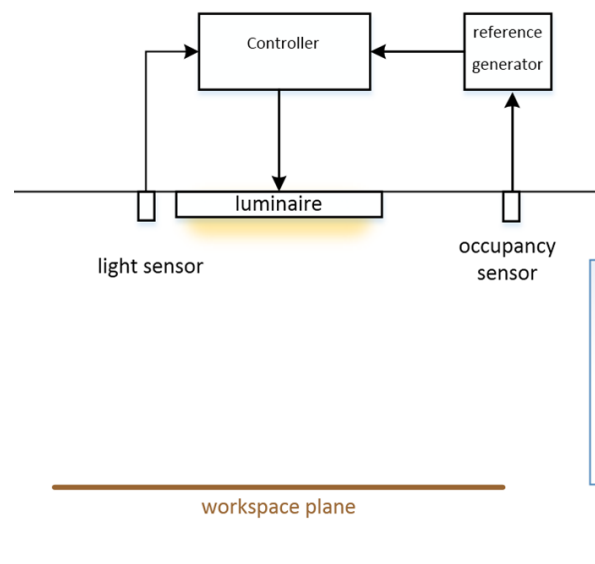


Fig. 2.3 High level diagram of the lighting control system under consideration.

A system composed by  $M$  luminaires and  $N$  workstations is studied and modelled in the following section.

## 2.1 Analytical model

Consider a lighting system with  $M$  ceiling-based luminaires. Each luminaire has a co-located light sensor and occupancy sensor and can communicate with a controller (Figure 2.4). Let the luminaires be dimmed using pulse width modulation

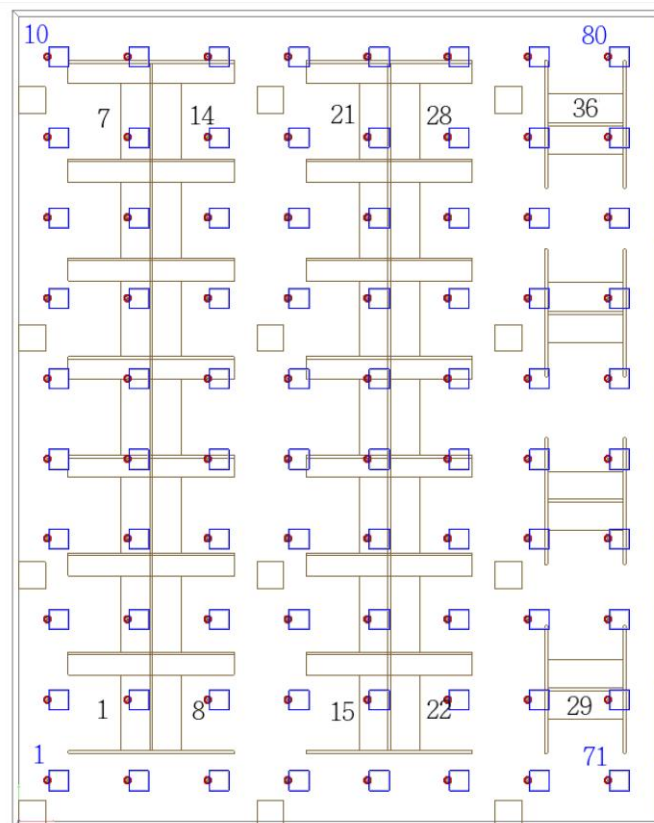


Fig. 2.4 Open-plan office lighting system with 80 luminaires (blue squares) with co-located light/occupancy sensors (red circles) and 36 zones. The windows are on the right side of the room.



(PWM). Let the  $m$ -th luminaire be dimmed linearly with duty cycle  $u_m(t)$  at time  $t$ , where  $0 \leq u_m(t) \leq 1$ . Under the linearity assumption that has been discussed, the power consumption of the luminaires may be approximated to be directly proportional to the dimming level. In this way, minimizing the power consumption of the entire system is equivalent to minimizing the 1-norm of the dimming vector  $\mathbf{u}(t) = [u_1(t), u_2(t), \dots, u_M(t)]^T$ ,

$$\|\mathbf{u}(t)\|_1 = \sum_{m=1}^M |u_m(t)| = \sum_{m=1}^M u_m(t). \quad (2.1)$$

The illumination value at the  $m$ -th sensor, in lux, at (continuous) time  $t$   $y_m(t)$  can be modelled as a linear combination of the artificial illumination and the daylight contribution [11]:

$$y_m(t) = \sum_{n=1}^M G_{m,n} u_n(t) + d_m(t), \quad m = 1, \dots, M \quad (2.2)$$

where  $G_{m,n}$  is the illuminance gain, which is the illuminance value at the  $m$ -th light sensor when the  $n$ -th luminaire is set at its maximum intensity, while all other luminaires are off and there is no other source of light;  $d_m(t)$  is the illuminance contribution at the  $m$ -th light sensor due to daylight at time  $t$ .

Let the workspace plane be divided into  $N$  logical zones, i.e. workstations. Similarly to (2.2), the average illumination value at zone  $j$  may be written as:

$$w_j(t) = \sum_{n=1}^M H_{j,n} u_n(t) + p_j(t), \quad j = 1, \dots, N \quad (2.3)$$

Here  $p_j(t)$  is the average illumination contributed at the  $j$ -th zone due to daylight at time  $t$ , while  $H_{j,n}$  is the average illumination of the  $j$ -th zone when the  $n$ -th luminaire is at its maximum, all other luminaires are off and there is no other source of light. The illumination gains  $G_{m,n}$  and  $H_{j,n}$  may be obtained with a night-time calibration step: without external light contribution each luminaire is dimmed at its maximum intensity and the corresponding light intensity is measured at the ceiling and at the workspace respectively. To clarify equations (2.2) and (2.3) consider Figure 2.5, where the time instants have been removed for simplicity.

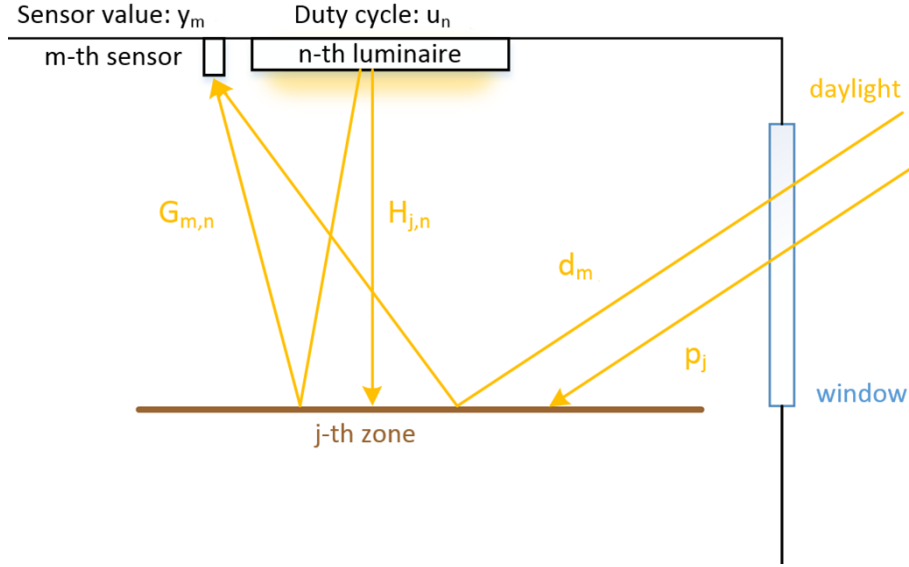


Fig. 2.5 Artificial and daylight contribution at the workspace plane and at the light sensor.

Each light sensor samples with the same sampling period  $T_s$  but the sampling is not synchronous across sensors. The illuminance value at light sensor  $m$  can thus be written in discrete time as:

$$y_m((k+1)T_s + \tau_m) = \sum_{n=1}^M G_{m,n}u_n(kT_s + \tau_m) + d_m((k+1)T_s + \tau_m) \quad m = 1, \dots, M \quad (2.4)$$

where  $\tau_m$  is a constant random delay,  $0 \leq \tau_m \leq T_s$  and  $k \in \mathbb{N}$ . The constant delay between sensors reflects the asynchronous nature of the system. Similarly to 2.4, the average illumination value at zone  $j$  in discrete time may be written as:

$$w_j((k+1)T_s + \tau_m) = \sum_{n=1}^M H_{j,n}u_n(kT_s + \tau_m) + p_j((k+1)T_s + \tau_m) \quad j = 1, \dots, N \quad (2.5)$$

Defining  $k \triangleq (kT_s + \tau_m)$  for brevity of notation, the whole model can be rewritten in matrix form as:

$$\begin{cases} \mathbf{y}(k+1) = \mathbf{G}\mathbf{u}(k) + \mathbf{d}(k+1) \\ \mathbf{w}(k+1) = \mathbf{H}\mathbf{u}(k) + \mathbf{p}(k+1) \end{cases} \quad (2.6)$$

Where:

$$\mathbf{G} = \begin{bmatrix} G_{1,1} & G_{1,2} & \dots & G_{1,M} \\ G_{2,1} & G_{2,2} & \dots & G_{2,M} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ G_{M,1} & G_{M,2} & \dots & G_{M,M} \end{bmatrix},$$

$$\mathbf{H} = \begin{bmatrix} H_{1,1} & H_{1,2} & \dots & H_{1,M} \\ H_{2,1} & H_{2,2} & \dots & H_{2,M} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ H_{N,1} & H_{M,2} & \dots & H_{N,M} \end{bmatrix},$$

$$\mathbf{y}(k) = [y_1(k), y_2(k), \dots, y_M(k)]^T,$$

$$\mathbf{u}(k) = [u_1(k), u_2(k), \dots, u_M(k)]^T,$$

$$\mathbf{d}(k) = [d_1(k), d_2(k), \dots, d_M(k)]^T,$$

$$\mathbf{w}(k) = [w_1(k), w_2(k), \dots, w_N(k)]^T,$$

$$\mathbf{p}(k) = [p_1(k), p_2(k), \dots, p_N(k)]^T.$$

In a practical scenario the illumination achieved by lighting control over the horizontal workspace plane is typically of interest in office lighting applications. A night-time calibration step is used to translate desired illuminance values over a zone to reference set-points at the ceiling located light sensors.

In this thesis two lighting control scenarios will be considered:

1. In the first scenario, labeled hereon as “sensor-driven lighting control” scenario, lighting control is achieved based only on sensor feedback. Thus the target illuminance over zones is translated into light sensor set-points based on local occupancy and target illuminance over a zone. For instance, the target may be  $W_o = 500$  lux and  $W_u = 300$  lux over a locally occupied and locally unoccupied/area occupied zone respectively, with the specific values chosen following European norms for office lighting [15].

2. In the second scenario, labeled hereon as “sensor-driven personal lighting control” scenario, lighting control is achieved based only on sensor feedback and user personal control inputs. A user may specify desired illuminance in his/her occupied zone and light sensor reference set-points are set accordingly.

# Chapter 3

## Control algorithms

In this chapter it is first explained how the reference set-points at light sensors are specified, then all the control algorithms considered in this thesis are discussed.

### 3.1 Reference set-points at light sensors

In the “sensor-driven lighting control” scenario, the set-points are computed using the measurements stored in the night-time calibration step by setting all the luminaires to maximum intensity, with no external light contribution. Let  $r_m$  denote the value at light sensor  $m$  and  $W$  denote the average illuminance value over the workspace plane. Then the light sensor set-point for locally occupied and locally unoccupied area, respectively denoted by  $r_{o,m}$  and  $r_{u,m}$ , are given by

$$\begin{aligned} r_{o,m} &= \frac{W_o \cdot r_m}{W}, \\ r_{u,m} &= \frac{W_u \cdot r_m}{W}, \end{aligned} \tag{3.1}$$

where  $W_o < W$  and  $W_u < W$  are the corresponding desired illuminance levels.

In the “sensor-driven personal lighting control” scenario, there may be light sensors associated to multiple zones. As such, there are multiple approaches to specify the reference set-points of these light sensors. Consider light sensor  $m$  that is associated with neighboring zones indexed by set  $\mathcal{N} = \{n_1, \dots, n_K\}$ . Consider  $n_k \in \mathcal{N}$  and let  $W_{n_k}$  denote the illuminance value desired by a user (this value can also be the default level  $W_o$  or  $W_u$  depending on the occupancy state over the zone) in zone  $n_k$ .

Three approaches are considered to specify the reference set-points at the shared light sensors.

- i) Minimum approach: the reference set-points at a shared light sensor  $m$  is specified as,

$$r_m^{(\min)} = \frac{\min_{n_k \in \mathcal{N}} W_{n_k} \cdot r_m}{W}. \quad (3.2)$$

In this case, the illuminance of the least demanding user is used to specify the set-points of the shared light sensors. This choice is expected thus to have lower power consumption.

- ii) Maximum approach: the reference set-points at a shared light sensor  $m$  is specified as,

$$r_m^{(\max)} = \frac{\max_{n_k \in \mathcal{N}} W_{n_k} \cdot r_m}{W}. \quad (3.3)$$

In this case, the illuminance of the most demanding user is used to specify the set-points of the shared light sensors, and this choice is expected to satisfy illuminance requirements of each user, if a solution is feasible.

- iii) Average approach: the reference set-points at the shared light sensors are selected as an average value as follows,

$$r_m^{(\text{ave})} = \frac{1}{K} \cdot \frac{\sum_{n_k \in \mathcal{N}} W_{n_k} \cdot r_m}{W}. \quad (3.4)$$

This choice should provide a trade-off between limiting the power consumption and satisfying illumination desired by users.

## 3.2 Reference stand-alone controller

The stand-alone controller proposed in [11] is used as a benchmark. In this work the authors address the multivariate control problem designing multiple stand-alone controllers where each controller evaluates its dimming level independent of each other. This means that the  $m$ -th controller seeks to achieve the reference set-point  $r_{o,m}$  if the  $m$ -th occupancy sensors determines local occupancy or the set-point  $r_{u,m}$  if the  $m$ -th occupancy sensors determines local unoccupancy.

### 3.2.1 Generalized stand-alone controller

The general form of a stand-alone controller can be described as follows [11]:

$$u_m(k) = \alpha_m e_m(k) + \beta_m u_m(k-1) + \gamma_m, \quad (3.5)$$

where  $u_m(k)$  is the dimming level for the  $m$ -th luminaire at time instant  $k$ ,  $\alpha_m$ ,  $\beta_m$ ,  $\gamma_m$  are constants in  $\mathbb{R}$ . In equation (3.5)  $e_m(k) = r_m(k) - y_m(k)$  is the error at the light sensor  $m$  at time instant  $k$  and  $r_m$  represents the reference set-point and can assume the value  $r_{o,m}$  or  $r_{u,m}$ .

The controller can also be described in state-space representation as follows:

$$\begin{cases} x_m(k+1) = \alpha_m e_m(k) + \beta_m x_m(k) + \gamma_m, \\ u_m(k) = \alpha_m e_m(k) + \beta_m x_m(k) + \gamma_m, \end{cases} \quad (3.6)$$

where  $x_m(k)$  represents the state, which is equal to  $u_m(k-1)$ . In equation (3.6) it had been disregarded that the luminaire dimming levels can take values only between 0 and 1, due to the physical limits of the luminaires. To satisfy this constraint, a saturation function is applied to each dimming level. That is, for  $j = 1, \dots, M$ :

$$S(u_j(k)) \triangleq \text{sat}(u_j(k)) = \begin{cases} 1, & \text{if } u_j(k) > 1 \\ u_j(k), & \text{if } 0 \leq u_j(k) \leq 1 \\ 0, & \text{if } u_j(k) < 0. \end{cases} \quad (3.7)$$

The saturated output of the controller is stored in memory and used to calculate the dimming level at the next iteration. The state space representation of the generalized controller can thus be written as:

$$\begin{cases} x_m(k+1) = S(\alpha_m e_m(k) + \beta_m x_m(k) + \gamma_m), \\ u_m(k) = S(\alpha_m e_m(k) + \beta_m x_m(k) + \gamma_m), \end{cases} \quad (3.8)$$

In the following sections, the stand-alone controller shall be analysed ignoring the effect of saturation for simplicity, as done in [11].

### 3.2.2 Stand-alone controller parameters

In [11] the authors derive the controller parameters according to the following procedure. Equation (2.4) can also be rewritten as:

$$y_m(k+1) = G_{m,m}u_m(k) + d_m(k+1) + \sum_{n \neq m} G_{m,n}u_n(k) \quad m = 1, \dots, M, \quad (3.9)$$

where again it has been set  $k \triangleq (kTs + \tau_m)$ . The last term in equation (3.9) represents the coupling term, that is the influence of other luminaires on the  $m$ -th luminaire. Neglecting the coupling term, equation (3.9) can be written as:

$$y_m(k+1) = G_{m,m}u_m(k) + d_m(k+1) \quad m = 1, \dots, M. \quad (3.10)$$

The controller aim is to let the illuminance value  $y_m(k)$  reach the set-point  $r_m(k)$ , so it is natural to choose:

$$r_m(k) = y_m(k+1) = G_{m,m}u_m(k) + d_m(k+1) \quad m = 1, \dots, M. \quad (3.11)$$

From this equation it is now possible to evaluate  $u_m(k)$ :

$$u_m(k) = \frac{r_m(k) - d_m(k+1)}{G_{m,m}} \quad m = 1, \dots, M. \quad (3.12)$$

The daylight term in (3.12) is in general not explicitly known. However under the assumption that daylight changes slowly within a control iteration, the value of daylight can be estimated from the previous iteration:

$$d_m(k+1) \approx d_m(k) = y_m(k) - G_{m,m}u_m(k-1) \quad m = 1, \dots, M. \quad (3.13)$$

Note that this is not a limiting assumption since typical values for each iteration are in the order of seconds. Substituting (3.13) in equation (3.12) it is possible to obtain the final expression for the controller:

$$u_m(k) = \frac{e_m(k)}{G_{m,m}} + u_m(k-1) \quad m = 1, \dots, M. \quad (3.14)$$

This equation can be written in the general form as in (3.5) by choosing:



$$\alpha_m = G_{m,m}^{-1}, \quad \beta_m = 1, \quad \gamma_m = 0.$$

With constant daylight and without coupling, this controller will achieve the reference in one step.

### 3.3 MIMO lighting control algorithm

The main part of this work has been the design of a Multi-Input Multi-Output (MIMO) controller that aims to achieve better performance with respect to the reference controller described in the previous section. It is considered a lighting controller whose objective is to minimize a weighted sum of squares of the illuminance errors at light sensors and square of the power consumption, while satisfying the following constraints:

- i) the illuminance value at each light sensor is above the reference set-point,
- ii) the dimming levels of the luminaires can only take values within physical limits.

The problem is addressed by considering two solutions that are discussed in the following subsections.

#### 3.3.1 Lighting control algorithm using unconstrained optimization

In the optimization framework, the following cost function is considered:

$$f(\mathbf{u}(k)) = \{\lambda \|\mathbf{y}(k+1) - \mathbf{r}\|_2^2 + (1 - \lambda) \|\mathbf{u}(k)\|_1^2\}, \quad (3.15)$$

where  $\mathbf{r} = [r_1, r_2, \dots, r_M]^T$  is the vector containing the reference set-points, the term  $\|\mathbf{y}(k+1) - \mathbf{r}\|_2^2$  is the square of the 2-norm of the difference between the vector with the light sensor values and the vector with the reference set-points. The second term  $\|\mathbf{u}(k)\|_1^2$  is the square of the power consumption (2.1). In (3.15),  $0 < \lambda \leq 1$  is a design parameter that balances the deviations of achieved illuminance at the light sensors from the reference set-points and with the power consumption. The optimum dimming vector is obtained as a solution to the unconstrained optimization problem:

$$\mathbf{u}^*(k) = \arg \min_{\mathbf{u}(k)} f(\mathbf{u}(k)). \quad (3.16)$$

Substituting the model  $\mathbf{y}(k+1) = \mathbf{G}\mathbf{u}(k) + \mathbf{d}(k+1)$  in (3.15) and solving the norm, the cost function can be rewritten as follows:

$$f(\mathbf{u}(k)) = \{ \lambda \mathbf{u}(k)^T \mathbf{G}^T \mathbf{G} \mathbf{u}(k) + 2\lambda \mathbf{u}(k)^T \mathbf{G}^T (\mathbf{d}(k+1) - \mathbf{r}) + (1 - \lambda) (\mathbf{u}(k)^T \mathbf{I})^2 + (*) \}, \quad (3.17)$$

where  $\mathbf{I} = [1 \dots 1]^T$  and  $(*)$  indicates terms that do not depend on  $\mathbf{u}(k)$ . The last term in (3.17) can also be written as:

$$(1 - \lambda) (\mathbf{u}(k)^T \mathbf{I})^2 = (1 - \lambda) (\mathbf{u}(k)^T \mathbf{I}) (\mathbf{I}^T \mathbf{u}(k)) = (1 - \lambda) \mathbf{u}(k)^T (\mathbf{I} \mathbf{I}^T) \mathbf{u}(k),$$

since  $\mathbf{u}(k)^T \mathbf{I}$  is a scalar term, so that the cost function (3.15) becomes:

$$f(\mathbf{u}(k)) = \{ \lambda \mathbf{u}(k)^T \mathbf{G}^T \mathbf{G} \mathbf{u}(k) + 2\lambda \mathbf{u}(k)^T \mathbf{G}^T (\mathbf{d}(k+1) - \mathbf{r}) + (1 - \lambda) \mathbf{u}(k)^T (\mathbf{I} \mathbf{I}^T) \mathbf{u}(k) \}. \quad (3.18)$$

Taking the derivative of (3.18) with respect to vector  $\mathbf{u}(k)$  and equating it to zero it yields:

$$\lambda \mathbf{G}^T \mathbf{G} \mathbf{u}(k) + \lambda \mathbf{G}^T (\mathbf{d}(k+1) - \mathbf{r}) + (1 - \lambda) (\mathbf{I} \mathbf{I}^T) \mathbf{u}(k) = 0, \quad (3.19)$$

and solving now the equation in  $\mathbf{u}(k)$ , it is possible to obtain the following optimum dimming vector:

$$\mathbf{u}^*(k) = (\mathbf{G}^T \mathbf{G} + \frac{1 - \lambda}{\lambda} \mathbf{I} \mathbf{I}^T)^{-1} \mathbf{G}^T (\mathbf{r} - \mathbf{d}(k+1)). \quad (3.20)$$

Generally it is not possible to assume that the daylight term in (3.20) is explicitly known. However under the assumption that daylight changes slowly, similarly to Section (3.2.2), we can estimate the daylight value from the previous iteration:

$$\mathbf{d}(k+1) \approx \mathbf{d}(k) = \mathbf{y}(k) - \mathbf{G}\mathbf{u}(k-1). \quad (3.21)$$

Then substituting (3.21) in (3.20) this final control law is obtained:

$$\mathbf{u}^*(k) = (\mathbf{G}^T \mathbf{G} + \frac{1 - \lambda}{\lambda} \mathbf{I} \mathbf{I}^T)^{-1} \mathbf{G}^T (\mathbf{e}(k) + \mathbf{G}\mathbf{u}(k-1)). \quad (3.22)$$

Where  $\mathbf{e}(k) = \mathbf{r} - \mathbf{y}(k)$  is the vector of errors at the time instant  $k$ .

In deriving this control law, the physical limits of the luminaire dimming levels were not accounted for. To make sure that the controller output is limited between 0 and 1 a saturation function is applied to the solution (3.22), as shown in (3.7).

### 3.3.2 Lighting control algorithm using constrained optimization

In the second approach the optimum dimming vector is obtained by adding the constraints on light sensors values and dimming levels explicitly. Then consider the optimization problem in (3.16) and add the following constraints:

$$\begin{cases} \mathbf{y}(k+1) = G\mathbf{u}(k) + \mathbf{d}(k+1) \geq \mathbf{r}, \\ \mathbf{0} \leq \mathbf{u}(k) \leq \mathbf{1}, \end{cases} \quad (3.23)$$

where the above inequalities hold component-wise,  $\mathbf{0}$  and  $\mathbf{1}$  are vectors with each component 0 and 1 respectively. The optimum dimming vector  $\mathbf{u}^*(k)$  is thus obtained by solving the following optimization problem at iteration  $k$ :

$$\mathbf{u}^*(k) = \arg \min_{\mathbf{u}(k)} \{ \lambda \|\mathbf{G}\mathbf{u}(k) + \mathbf{d}(k+1) - \mathbf{r}\|_2^2 + (1 - \lambda) \|\mathbf{u}(k)\|_1^2 \}, \quad (3.24)$$

$$\begin{cases} \mathbf{y}(k+1) = G\mathbf{u}(k) + \mathbf{d}(k+1) \geq \mathbf{r}, \\ \mathbf{0} \leq \mathbf{u}(k) \leq \mathbf{1}, \end{cases} \quad (3.25)$$

Note that the above optimization problem always has a feasible solution for the “sensor-driven lighting control” scenario, given that  $\mathbf{d}(k) \geq \mathbf{0}$  and  $G\mathbf{1} \geq \mathbf{r}$  holds due to the calibration step. Note also that the illumination error is captured in both the first term of the cost function as well as in the first constraint. This ensures that the attained light sensor values at the optimum solution will be close to the set-points, as opposed to an optimizing solution where this term is not taken into account in the cost function ( $\lambda = 0$  case).

Again, in the optimization framework, the daylight term in (3.24) and in (3.25) is not explicitly known. However, under the assumption that the daylight changes slowly, this term may be estimated again using (3.21).

Note finally that the cost function in (3.24) is quadratic in the dimming levels and the inequality constraints are linear in the dimming levels. Such optimization

problems can be solved to determine the optimum dimming vector using efficient quadratic programming algorithms like the interior-point and variants [20].

# Chapter 4

## Numerical results

In this chapter simulation results are shown to evaluate and compare the performance of the proposed control algorithms with the reference stand-alone controller, under the two considered control scenarios. The performance are evaluated in terms of transient and steady-state behaviour, in particular overshoot and settling time are shown. Energy consumption of the entire system and under-illumination over a day are also considered. The office lighting model was created in DIALux [23], for a detailed description of the example model, please refer to [11].

### 4.1 Office lighting model and parameter description

The office model is depicted in Figure 4.1. It has length 24 m and width 19 m with height of the ceiling of 2.6 m. There are  $M = 80$  luminaires (blue rectangles) and sensors (red circles) organized in a grid of 10 by 8 and indexed by blue numbers. The half-opening angle of the occupancy sensors is approximately  $45^\circ$ ; when a user falls in its field-of-view the sensor detects the presence. The workspace plan is divided into  $N = 36$  zones, indexed by black numbers, representing the office work areas. The room is oriented  $110^\circ$  North.

Two scenarios are considered. In the first scenario, localized illumination adapted to occupancy and light sensor inputs is considered to provide a default average illuminance value of  $W_o = 500$  lux over an occupied zone and  $W_u = 300$  lux over an unoccupied zone, with light sensor reference set-points defined accordingly. In the second scenario, we consider personal control wherein the light sensor set-points are

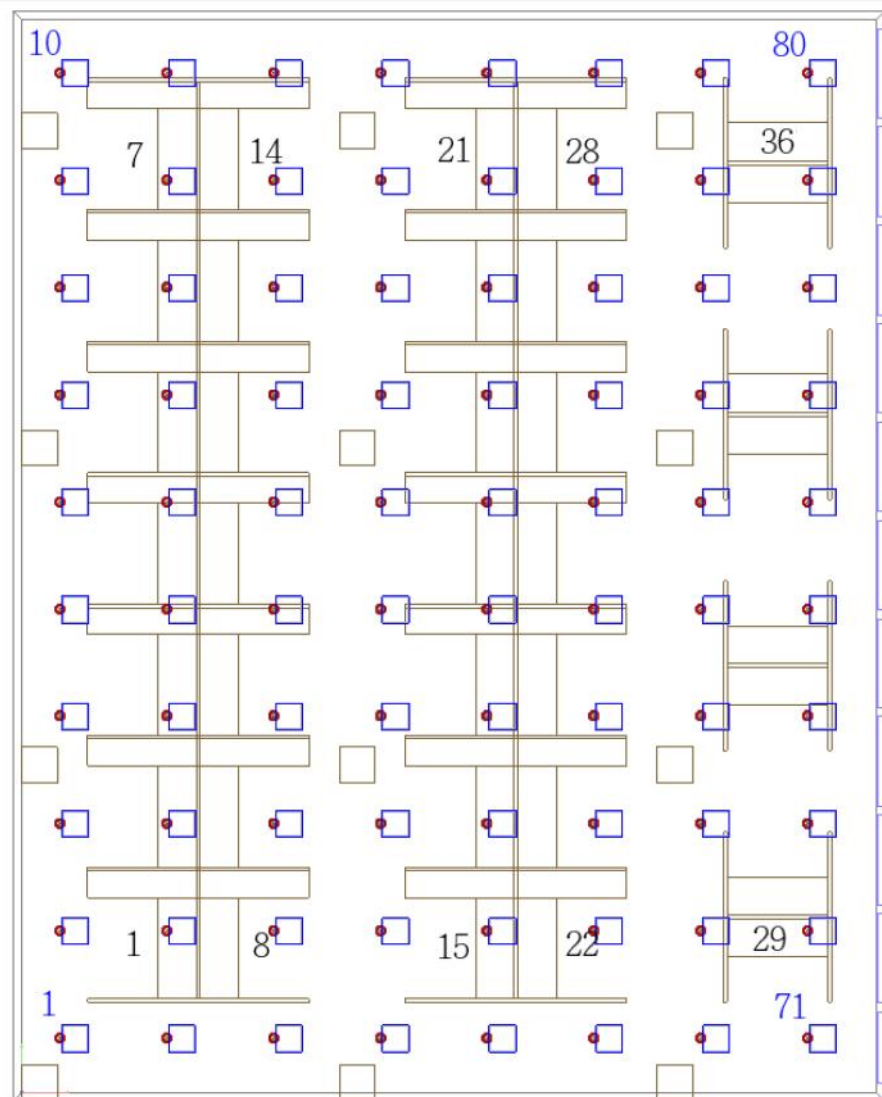


Fig. 4.1 Open-plan office lighting system with 80 luminaires (blue squares) with co-located light/occupancy sensors (red circles) and 36 zones. The windows are on the right side of the room.

modified in order to satisfy user illumination personal control requests. In the model, when all the luminaires are set to 0.85 an average illumination of 500 lux is achieved.

The office has windows on one side of the room for daylight. A clear sky daylight model is considered in the simulations. The light sensors send their measurement every one second to the controller. The asynchronous behaviour of the sensors is modeled by adding a random delay with value between 0 and 1 in the initialization time. The proposed controller waits for all the sensor measurements before computing the new dimming level while the stand-alone controller evaluates the dimming level once it receives the associated sensor measurement.

## 4.2 Unconstrained optimization behaviour

First, results related to the unconstrained control algorithm are shown. The reason why the unconstrained optimization is considered by itself is that it has an intrinsic problem, related to daylight.

Two scenarios will be showed to explain this behaviour:

- i) When all the 36 zones are occupied by users,
- ii) When only the seventh zone is occupied.

For these representative simulations the parameter  $\lambda$  will be set to 0.5 and a time snap-shot at 11 am with daylight will be considered as an example.

### 4.2.1 All-occupied scenario

In Figure 4.2, 4.3 and 4.4 the steady-state values of illuminance at the zones, the dimming levels and the illuminance at the sensors are depicted respectively. From Figure 4.2 it is possible to see that from zone 22 to zone 36 the illuminance values are much higher than the desired value. This behaviour is due to two factors:

- 1) the daylight contribution (note that the mentioned zones are the closest to the windows),
- 2) the dimming levels saturation to the maximum value 1.

As a matter of fact, from Figure 4.3 it is easy too see that many luminaires, from luminaire 51 to 69 in particular, are saturating to 1. This behaviour is certainly undesired, since it is only providing a surplus of illuminance where actually an

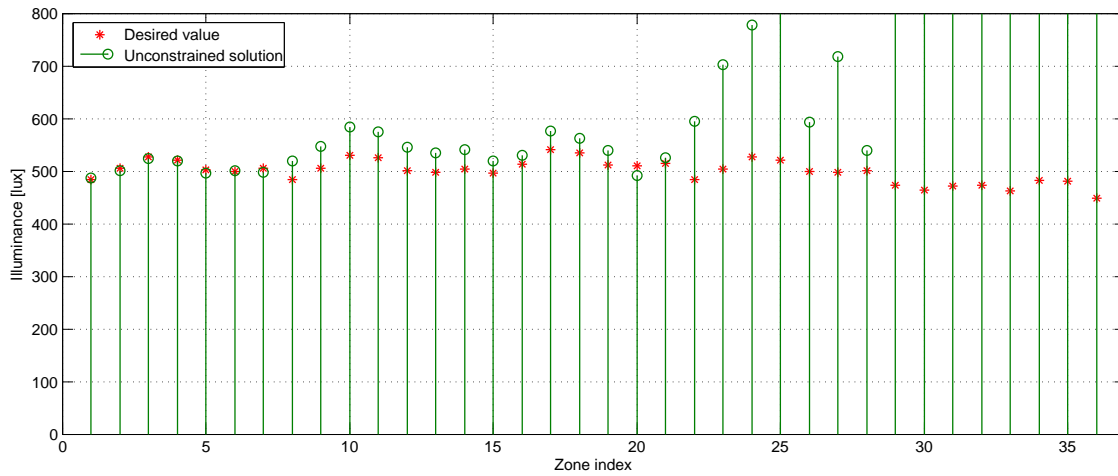


Fig. 4.2 Steady-state value of the illuminance at zones, daylight at 11 a.m., all zones occupied. Values higher than 800 lux are not shown for plots legibility.

artificial contribution is not needed at all. This wrong behaviour can also be better understood from Figure 4.4 where the illuminance at the sensors is plotted. Since many sensors (in particular from 60 to 80) are sensing a very high illuminance value it is natural to expect the near luminaires to be set to zero or, at least, to a very low dimming level. Instead, as said above, many of them are dimmed at their maximum value, leading to a significant waste of energy.

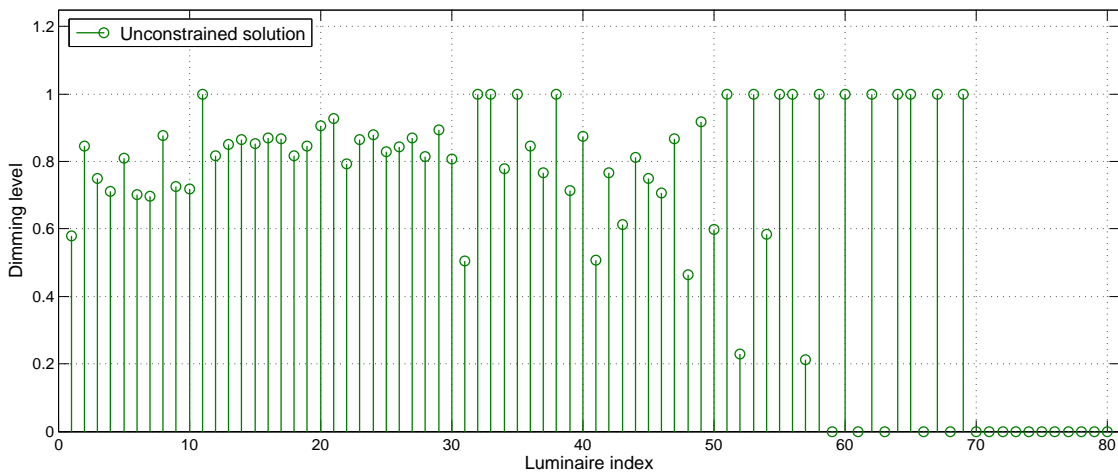


Fig. 4.3 Steady-state value of the luminaires dimming levels, daylight at 11 a.m., all zones occupied.



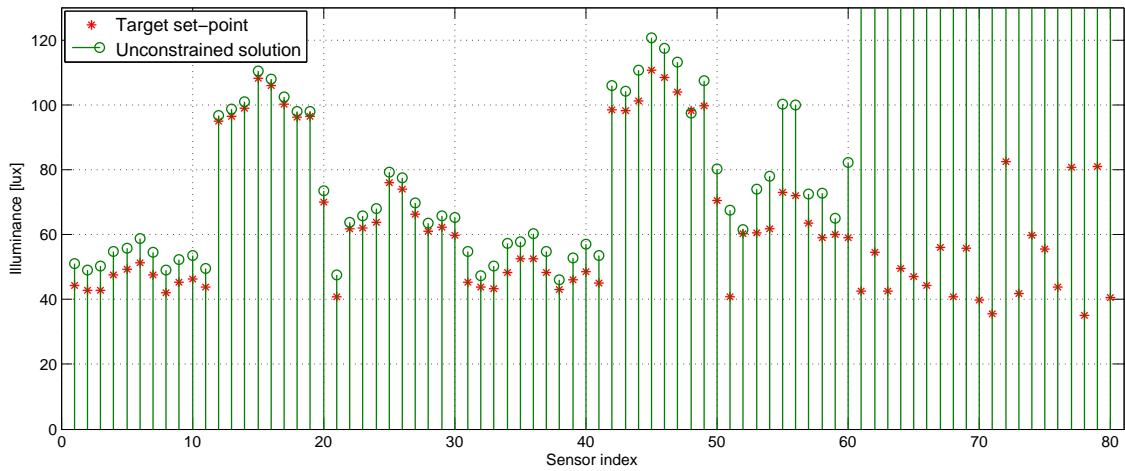


Fig. 4.4 Steady-state value of the illuminance at sensors, daylight at 11 a.m., all zones occupied. Values higher than 130 lux are not shown for plots legibility.

#### 4.2.2 One-occupied scenario

This effect is even more evident if only one zone in the office is occupied, suppose for example the seventh zone. Again, in Figure 4.5, 4.6 and 4.7 the steady-state values of illuminance at zones, dimming levels and illuminance at sensors are respectively depicted for this scenario. The sensors triggered by the occupancy at the seventh

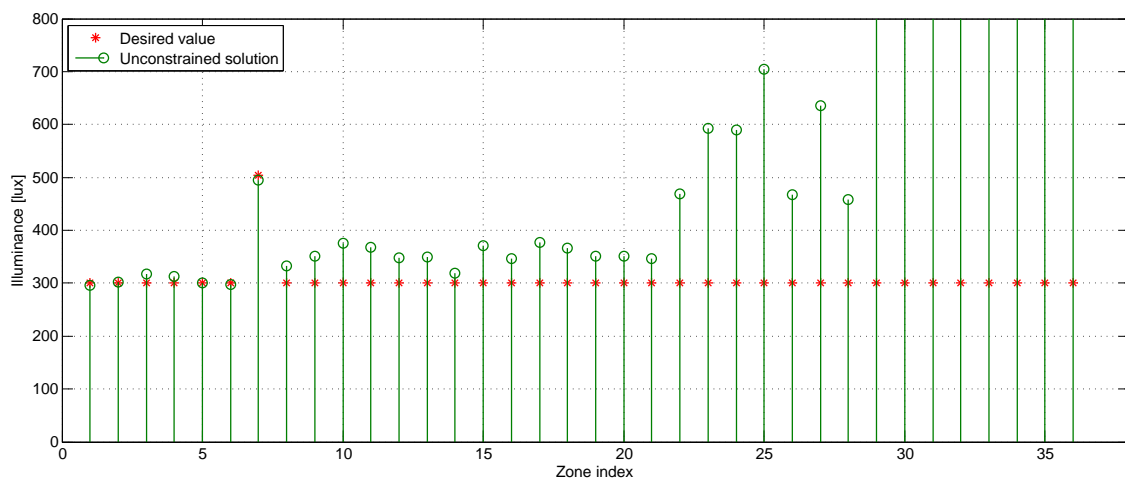


Fig. 4.5 Steady-state value of the illuminance at zones, daylight at 11 a.m., zone 7 occupied.

zone are: 9, 19 and 20. From Figure 4.6 it is possible to see that the behaviour

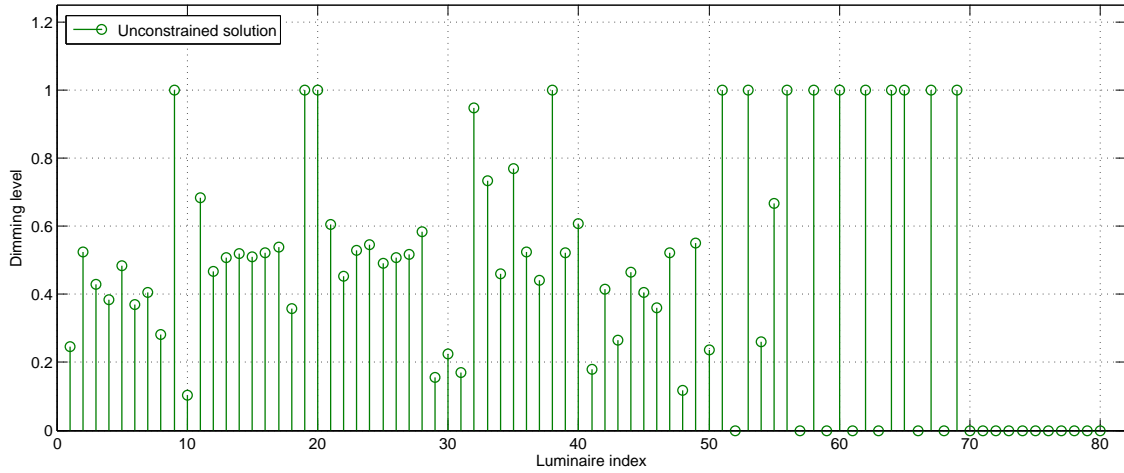


Fig. 4.6 Steady-state value of the luminaires dimming levels, daylight at 11 a.m., zone 7 occupied.

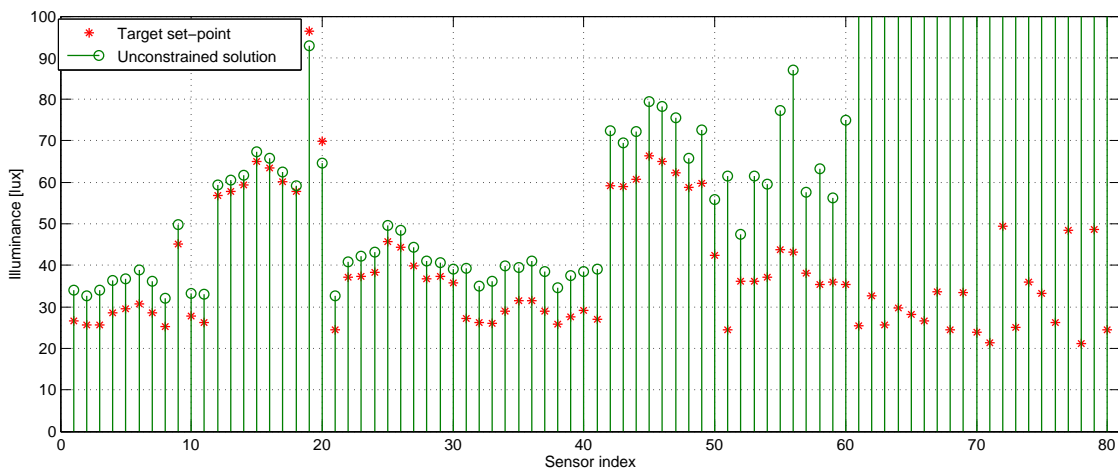


Fig. 4.7 Steady-state value of the illuminance at sensors, daylight at 11 a.m., zone 7 occupied.

is similar to the one shown in the previous subsection: luminaire 9, 19 and 20 are correctly saturating to 1 in order to let the related sensors reach their set-points; on the other hand many luminaires closer to the windows are saturating, even if their related occupancy sensors are not triggered by the presence of some users. Thus, with this control law, a lot of energy is wasted.

### 4.2.3 Explanation and energy savings

The reason behind this behaviour is that the physical constraint on the dimming levels has not been taken into account in deriving the control law, i.e. the saturation function is applied only once that the control law is evaluated. To better understand this behaviour, consider the optimum dimming vector obtained in equation (3.22):

$$\mathbf{u}^*(k) = (G^T G + \frac{1-\lambda}{\lambda} \mathbf{I} \mathbf{I}^T)^{-1} G^T (\mathbf{e}(k) + G\mathbf{u}(k-1)). \quad (4.1)$$

For notation simplicity, suppose to choose  $\lambda = 1$ , the optimum dimming vector thus becomes:

$$\mathbf{u}^*(k) = (G^T G)^{-1} G^T (\mathbf{e}(k) + G\mathbf{u}(k-1)) = G^{-1} (\mathbf{e}(k) + G\mathbf{u}(k-1)) = G^{-1} \mathbf{e}(k) + \mathbf{u}(k-1). \quad (4.2)$$

The  $j$ -th dimming level can be written as:

$$u_j(k) = u_j(k-1) + a_{j,j}(r_j(k) - y_j(k)) + \sum_{m=1, m \neq j}^M a_{j,m}(r_m(k) - y_m(k)) \quad (4.3)$$

where  $a_{j,m}$  is the element in position  $j, m$  of  $G^{-1}$ . When huge daylight is entering the room, the sensed values  $y_m$  of luminaires close to the windows are very high (around 6000/7000 lux); this implies a large negative error  $e_m(k) = r_m(k) - y_m(k)$ . Moreover, many terms  $a_{j,m}$  in the inverse of  $G$  are negative as well, leading to a very high dimming level that is then saturated to 1. This behaviour is clearly against the natural and intuitive idea to set to zero the dimming levels when the daylight contribution is very high.

Similar behaviours were found in all the hours characterized by huge daylight values. To show the high energy consumption provided by the unconstrained optimization consider figure 4.8 where the energy savings of the reference stand-alone controller and the unconstrained solution are shown over a day. The energy savings are evaluated by comparing with a system with all luminaires fixed at a dimming level of 0.85 and with all the zones occupied during the whole day. In this simulation the highest daylight contributions are concentrated from 9 a.m. to 2 p.m.. It is easy to see how the proposed unconstrained solution is using much more energy with respect to the reference controller, especially when the daylight contribution is higher. Thus,

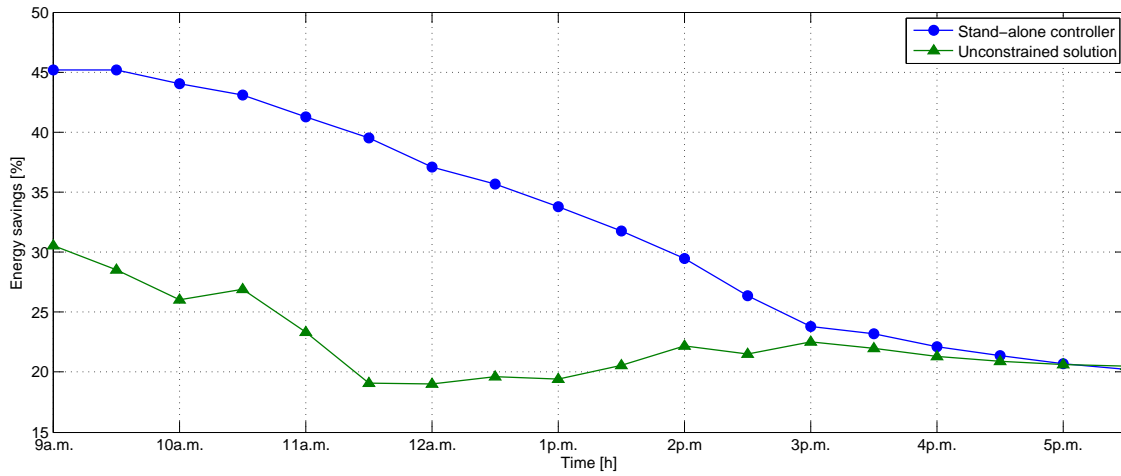


Fig. 4.8 Comparison of energy savings

the approach in designing the lighting controller from an unconstrained optimization problem is undesirable and in the following sections only the constrained solution will be considered.

### 4.3 Sensor-driven lighting control

In the following subsection the constrained optimization is analysed and compared with the reference stand-alone controller proposed in [11]. In particular, these comparisons will be made on:

- Overshoot and settling time,
- Transient period,
- Achieved illuminance and energy savings over a day,
- All zones occupied in a specific scenario,
- Only one zone occupied in a specific scenario.

#### 4.3.1 Overshoot/undershoot and settling time

In Figure 4.9 the transient period of the two controllers is depicted, showing as an example the illuminance value over zone 17, which goes from local unoccupancy to

occupancy at  $t = 0$ . In this simulation there is daylight at 10 am. It is clear that the constrained solution shows no overshoot/undershoot while the stand-alone controller has overshoot of approximately 18% and undershoot of approximately 10%. The overshoot and undershoot are respectively defined as the maximum and minimum values in the transient response compared to the final steady-state value. Secondly,

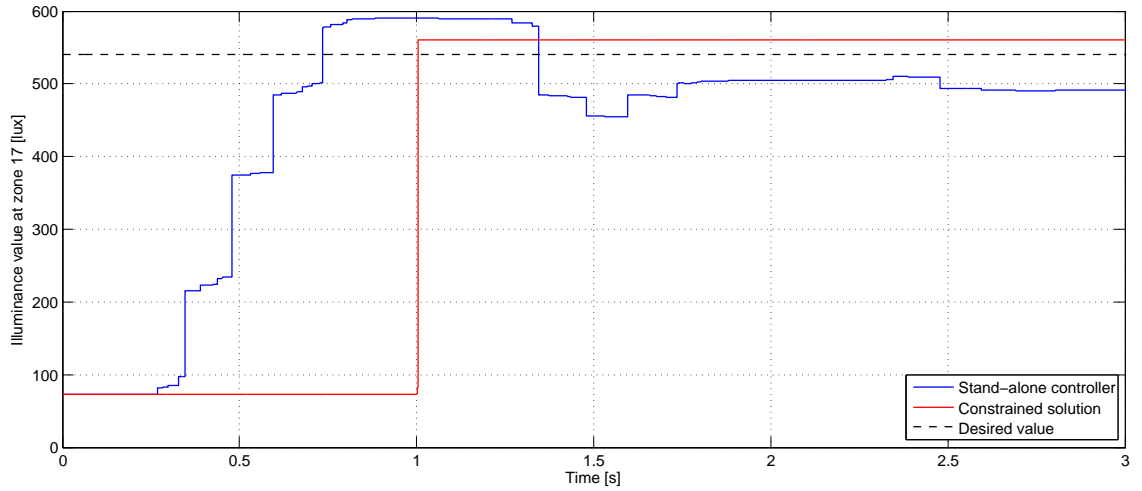


Fig. 4.9 Transient behaviour of the controllers.

statistical behaviour is considered with a run of 1000 simulations starting from zero state, when all the luminaires are off and considering daylight at 10 am. At  $t = 0$ , an occupancy step is simulated for each zone (i.e.  $r_m = r_{o,m}, \forall m$ ), then the overshoot and the settling time are collected for each zone. The settling time is the time that the illuminance needs to reach and remain inside a 5% threshold of the final steady-state value. In these simulations, the gain  $\alpha_m$  of all  $M$  stand-alone controllers is varied while the gain  $\beta_m$  is left unchanged at 1. In this way, it is possible to see a trade-off between average overshoot and settling time. In Figure 4.10, the average overshoot at each zone is plotted comparing the constrained solution with the reference stand-alone controller for three different values of the gain  $\alpha_m$ . The proposed controller does not show any overshoot while in some zones the average overshoot obtained with the stand-alone controller is higher than 20%. Moreover, to be close to the overshoot performance of the constrained solution, the gains  $\alpha_m$  of the stand-alone controller have to be reduced (see  $\alpha_m = G_{m,m}^{-1}/3$  case). Such modification however results in an increase in the settling time, as can be seen in Figure 4.11. These values, with sensor

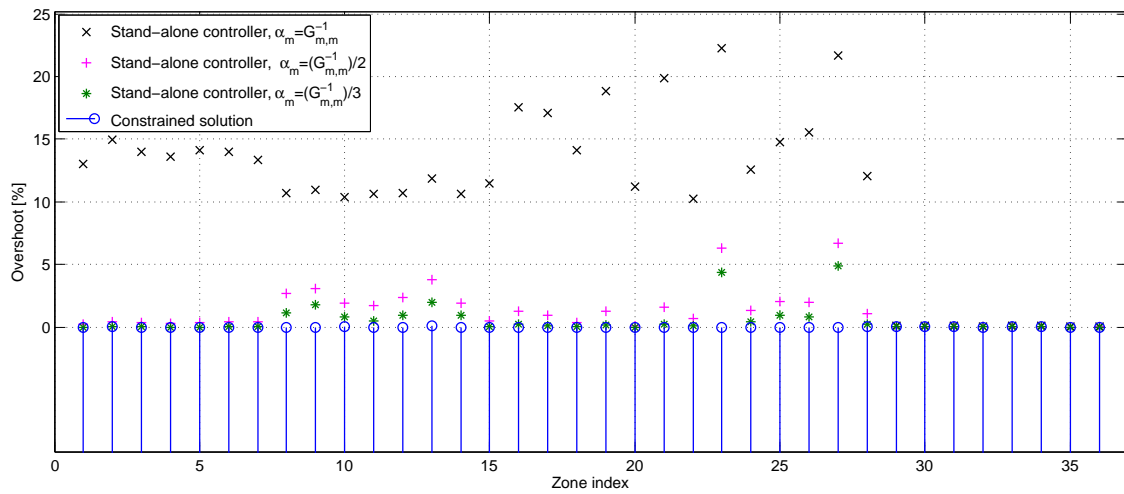


Fig. 4.10 Average overshoot of illumination at each zone for different values of the gain  $\alpha_m$  (1000 simulations for each case).

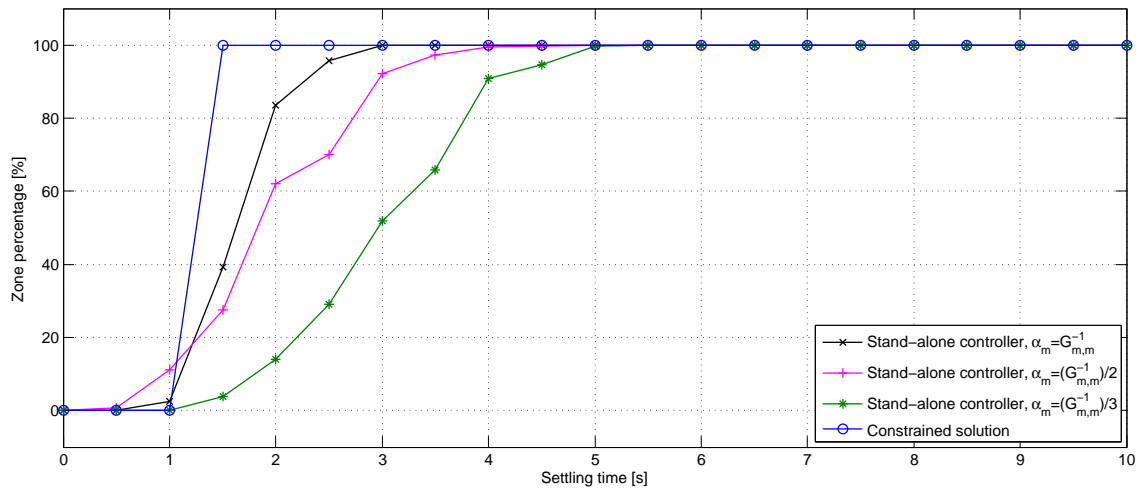


Fig. 4.11 Settling time for different values of the gain  $\alpha_m$  (1000 simulations for each case).

sampling period chosen to be 1 second, are still small enough for appropriate lighting control behaviour. In Table 4.1, it is then shown the percentage of zones that reached the steady-state value in 2 seconds. It is clear that the proposed constrained solution performs better than the reference controller in dealing with overshoot/undershoot and has a smaller settling time.

Controller	Zone percentage
Constrained solution	100%
Stand-alone controller, $\alpha_m = G_{m,m}^{-1}$	82%
Stand-alone controller, $\alpha_m = G_{m,m}^{-1}/2$	63%
Stand-alone controller, $\alpha_m = G_{m,m}^{-1}/3$	16%

Table 4.1 Percentage of zones that reached the steady state value in 2 seconds (1000 simulations for each case).

### 4.3.2 Achieved illuminance and energy savings

In this subsection the performance in terms of achieved illuminance and energy savings are evaluated.

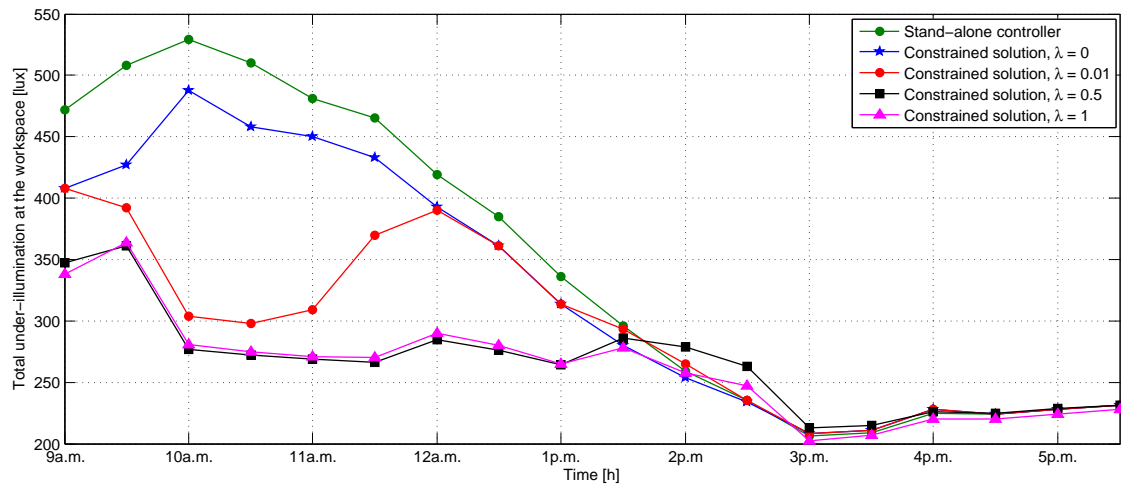


Fig. 4.12 Comparison of total under-illumination over all zones.

In Figures 4.12 and 4.13, there are shown respectively the total under-illumination at the workspace and the energy savings over a day with different daylight conditions when all the zones are occupied. The total under-illumination at the workspace is obtained by considering the under-illumination in each zone and aggregating these values. In these plots, different values of parameter  $\lambda$  in the constrained solution are considered. From Figure 4.13, it is possible to note that the energy savings from the stand-alone controller and the proposed controller are approximately the same, for all the values of  $\lambda$  considered. On the other hand, from Figure 4.12 it is clear that the

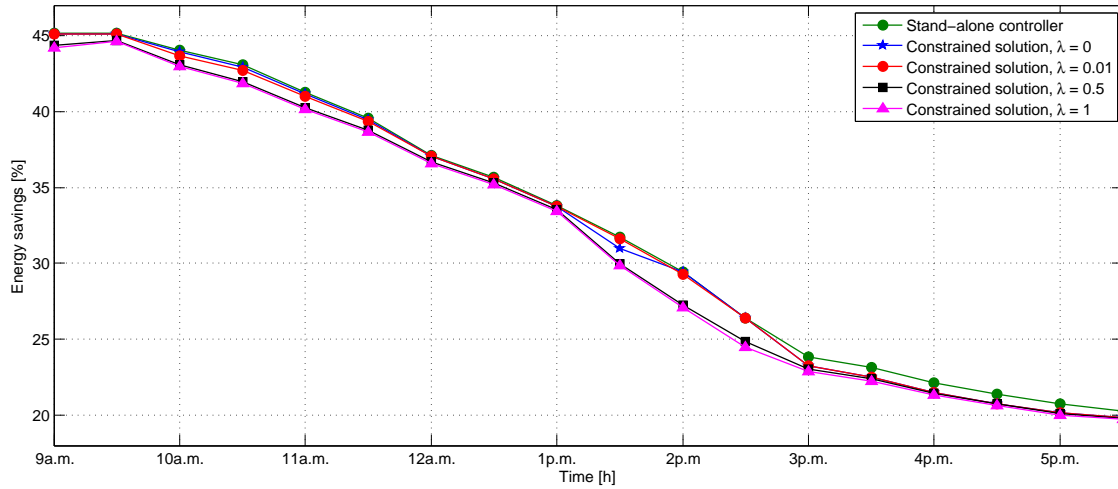


Fig. 4.13 Comparison of energy savings.

total under-illumination is much less than the proposed controller, in particular by choosing  $\lambda = 0.5$  and  $\lambda = 1$ .

### 4.3.3 All zones occupied

Similarly to section 4.2, it is now considered a scenario where all the zones are occupied and there is daylight at 10 a.m. In these and all the following simulations,  $\lambda$  has been set to 0.5 since, as seen in section 4.3.2, this choice provides a good trade-off between under-illumination and energy savings. In Figure 4.14, 4.15 and 4.16 are depicted the steady-state values respectively of illuminance values over the zones, dimming levels of the luminaires and illuminance values at the light sensors under this scenario. It is possible to note from Figure 4.14 that the stand-alone controller leads to under-illumination over zones 15-21. On the other hand, the proposed constrained solution performs better leading to a higher illumination over these zones. In particular observe zone 21 where with the constrained optimization the desired value is exactly reached. These zones are roughly in the middle column of the room. The proposed optimization works better since many luminaires are set to an higher dimming level, in particular observe luminaires from 42 to 50.



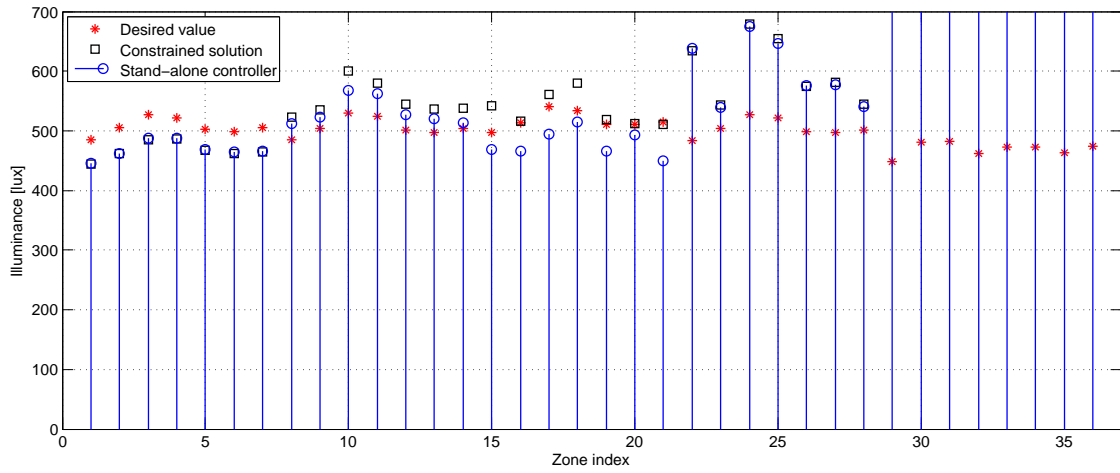


Fig. 4.14 Comparison of illuminance values at zones in steady-state, all zones occupied, daylight 10 a.m..

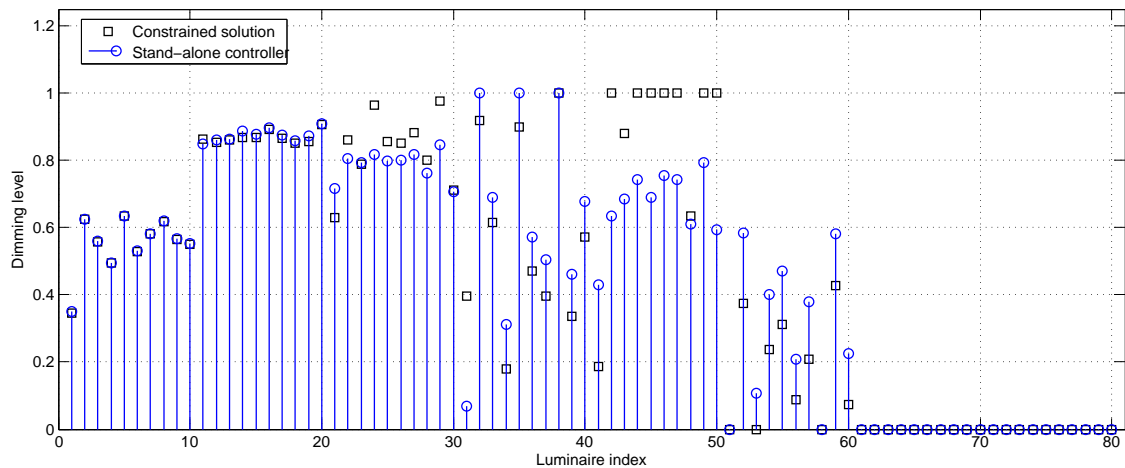


Fig. 4.15 Comparison of dimming levels of luminaires in steady-state, all zones occupied, daylight 10 a.m..

### 4.3.4 One zone occupied

The last scenario considered in the sensor-driven lighting control section is when only one zone is occupied and there is still daylight at 10 a.m.. Suppose as example that the twentieth zone becomes occupied at  $t = 0$  while all the other zones are unoccupied. In Figure 4.17, 4.18 and 4.19 are shown steady-state values respectively of illuminance values over the zones, dimming levels of the luminaires and illuminance values at

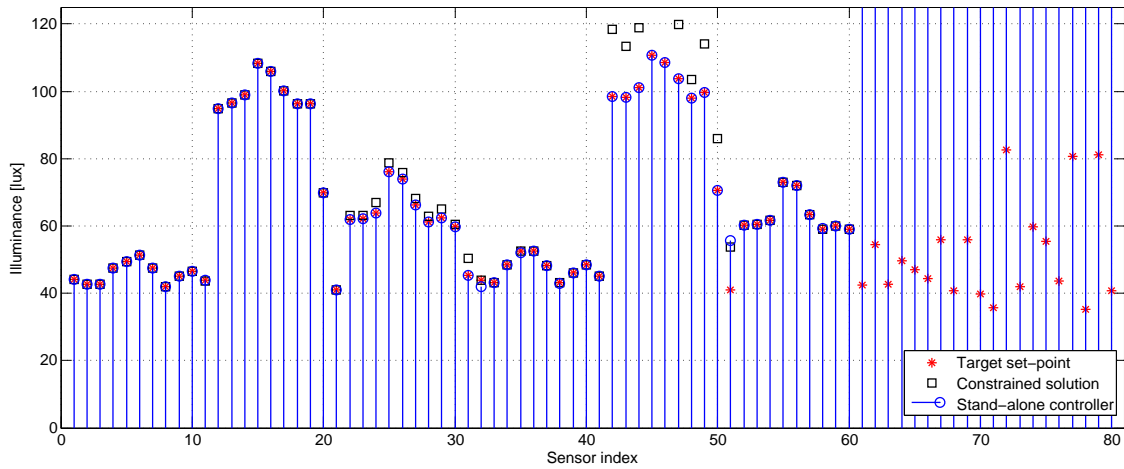


Fig. 4.16 Comparison of illuminance values at light sensors in steady-state, all zones occupied, daylight 10 a.m..

the light sensors for this scenario. From Figure 4.17 it is possible to see that the

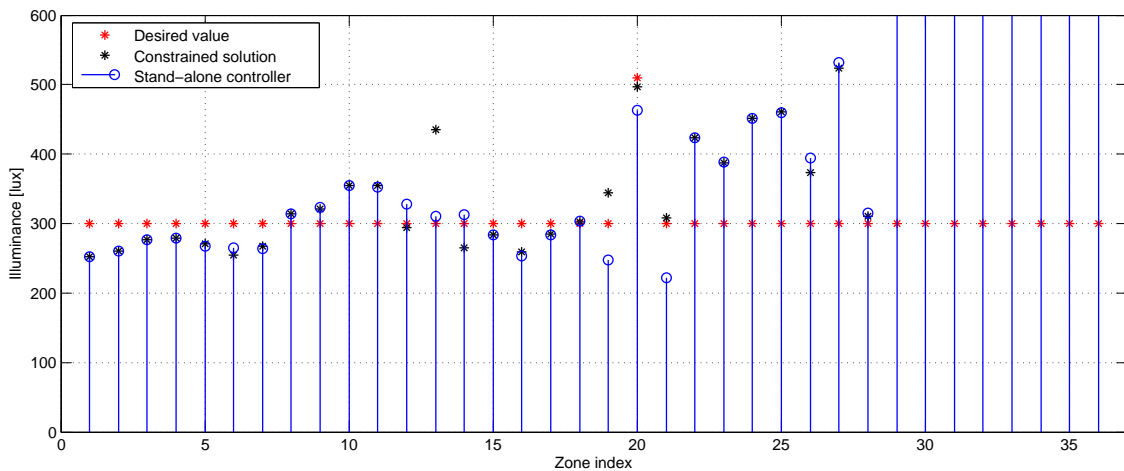


Fig. 4.17 Comparison of illuminance values at zones in steady-state with local occupancy over zone 20, daylight 10 a.m..

stand-alone controller leads to under-illumination in zone 20, while the constrained solution is much closer to the desired value. Also note the illuminance values at sensors 38 and 48, which are triggered due to occupancy in zone 20, from Figure 4.19. The stand-alone controller fails to reach the reference set-point at sensor 38 while achieving the reference set-point at sensor 48; the constrained solution is able

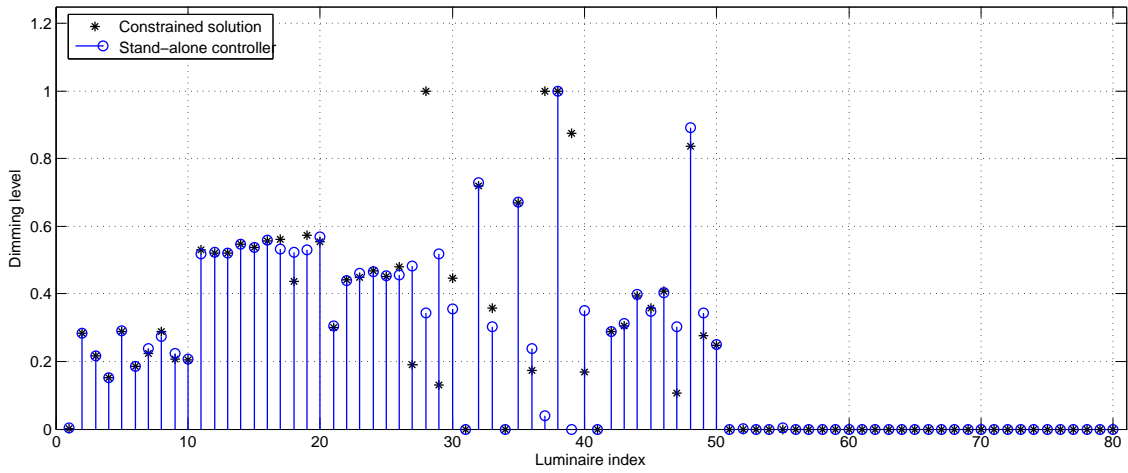


Fig. 4.18 Comparison of dimming levels of luminaires in steady-state with local occupancy over zone 20, daylight 10 a.m..

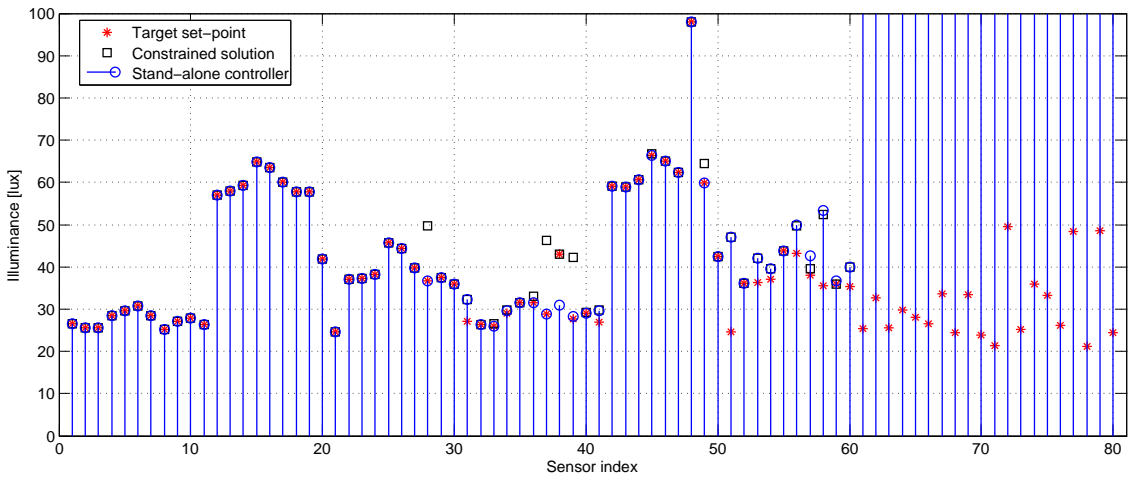


Fig. 4.19 Comparison of illuminance values at light sensors in steady-state with local occupancy over zone 20, daylight 10 a.m..

instead to achieve the reference set-point at both these light sensors. This happens since luminaires 37 and 39 are at a much higher dimming level in the constrained solution than in the stand-alone controller resulting in higher illuminance at zone 20 and at corresponding light sensors.

## 4.4 Sensor-driven personal lighting control

In this section the performance of the proposed constrained optimization in the personal control scenario are evaluated. Consider the following scenario: at  $t = 0$  two neighbouring zones get occupied while all the other zones are unoccupied and there is no daylight. In particular consider zone 18 and 25 and suppose that the two occupants require 600 lux and 400 lux respectively. In Figures 4.20, 4.21 and 4.22 it is shown the steady state value of the average illuminance at zones with the minimum, maximum and average approaches respectively as described in section 3.1. Note that with the reference controller for all the three approaches there are 100 lux or more of under-illumination over zone 18, while with the constrained solution an illumination value close to the desired 600 lux is obtained.

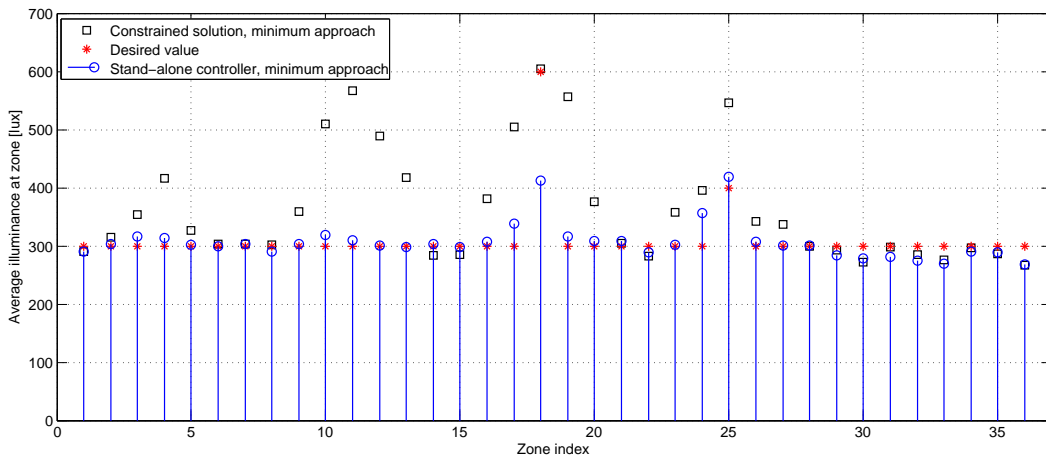


Fig. 4.20 Steady-state value of the illuminance at zones with the minimum approach.

To better understand the performance of the proposed controller, under the same occupancy scenario consider also the steady-state values of illuminance over zones (Figure 4.23) and at light sensors (Figure 4.24) and dimming levels of luminaires (Figure 4.25) for the maximum approach of setting set-points. In this simulation daylight at 5 p.m. is also considered. In Figure 4.23, it is possible to see that the desired illuminance value over zone 18 can be met with the proposed controller, while the stand-alone controller under-illuminates this zone. From Figure 4.24, observe the illuminance values at light sensors 36, 45 and 46, which are triggered due to occupancy in zone 18. It is clear that the stand-alone controller fails to meet the

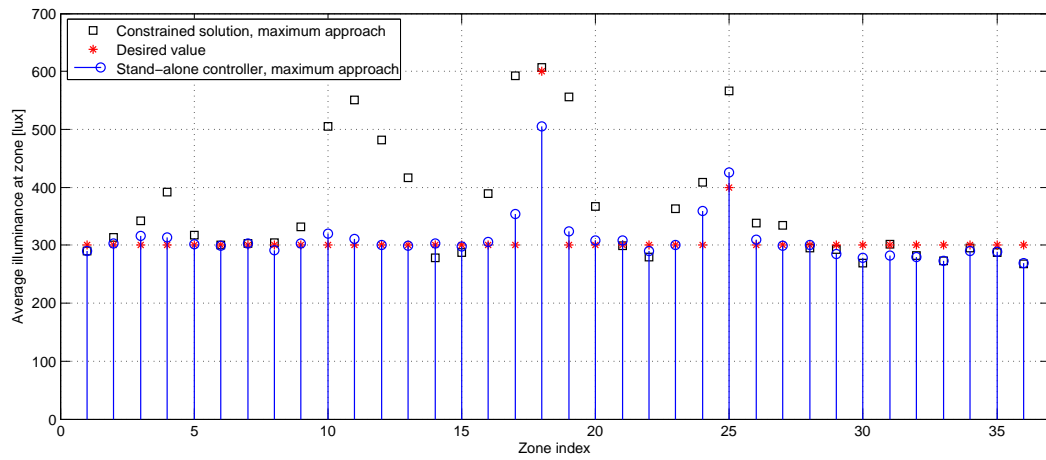


Fig. 4.21 Steady-state value of the illuminance at zones with the maximum approach.

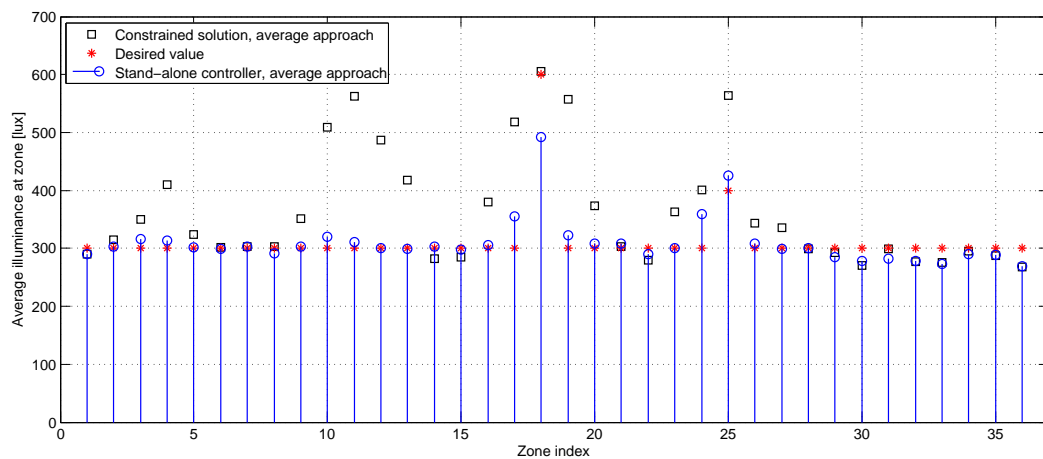


Fig. 4.22 Steady-state value of the illuminance at zones with the average approach.

reference set-points at these sensors, while they are exactly reached with the proposed controller. This is a result of imposing that the illuminance value be no smaller than the set-point as a constraint as well as a penalty term in the cost function of the constrained optimization problem, which enforces the solution to one where the sensor constraints are tightly met. This results in the neighbouring luminaires being at a much higher dimming level in the constrained solution compared to the reference stand-alone controller; in particular from Figure 4.25 observe the luminaires 25, 26, 34, 35, 37, 55 and 56. This leads to a much higher illumination value over zones 18 and 25, as observed from Figure 4.23.

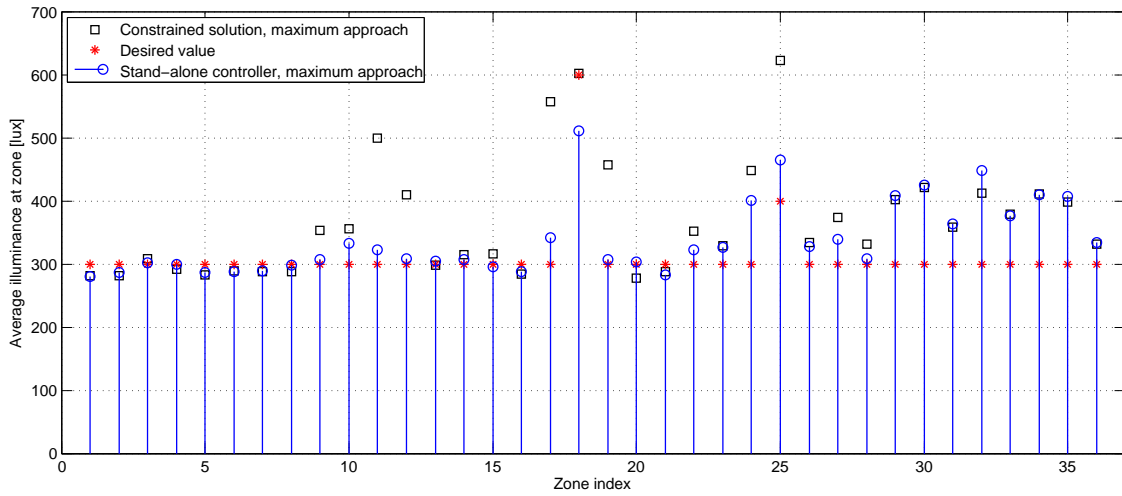


Fig. 4.23 Steady-state value of the illuminance at zones with the maximum approach, daylight at 5 p.m..

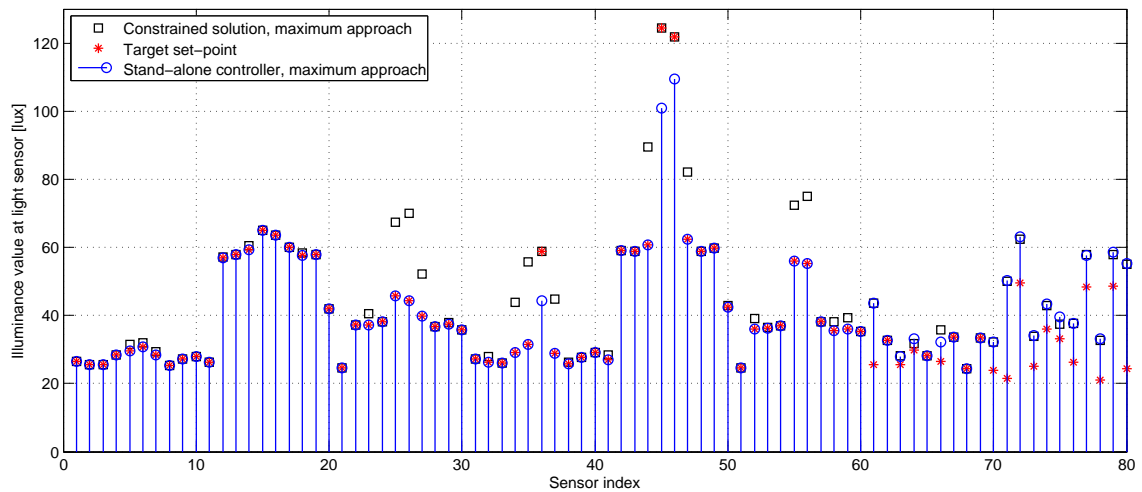


Fig. 4.24 Steady-state value of illuminance at light sensors with the maximum approach, daylight at 5 p.m..

Simulations are now considered to show statistical validity of our results. Consider again the same occupancy scenario but now suppose that the occupant at the 25-th zone can select the desired illuminance level at zone with a value in the range (400, 600) lux. The occupant at zone 18 requires again 600 lux. In Figure 4.26 and 4.27 we show the difference between the achieved illuminance and the desired value at zones for the stand-alone controller and the proposed controller respectively. For both

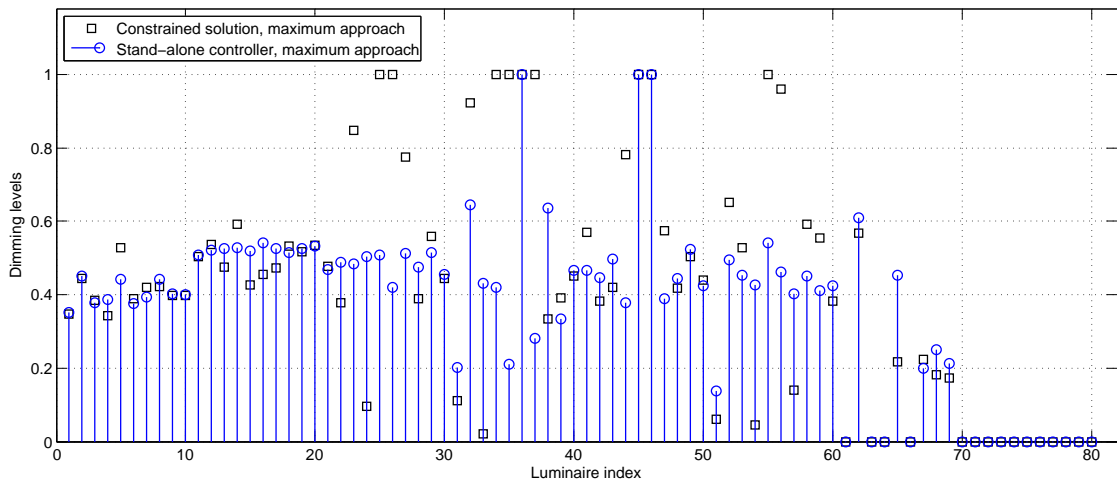


Fig. 4.25 Steady-state value of dimming levels with the maximum approach, daylight at 5 p.m..

control laws, 1000 simulations are run and the minimum approach is shown. The box plot shows the median as the red line, the 75-th and 25-th percentile values as the box boundaries, and points outside 1.5 times the size of the box are displayed individually by red crosses [29]. From Figure 4.26, it can be observed that for all the illuminance values required at zone 25, the reference controller shows a large under-illumination at zone 18, while with the proposed controller the desired value is met in each simulation. Across simulation instances, note from Figure 4.27 that the illuminance values achieved in zones that are neighboring to zone 25 depend on the desired illuminance value over zone 25. This is because of the intrinsic design of the proposed controller wherein neighbouring luminaires also would dim to satisfy the reference set-points of light sensors over a zone.

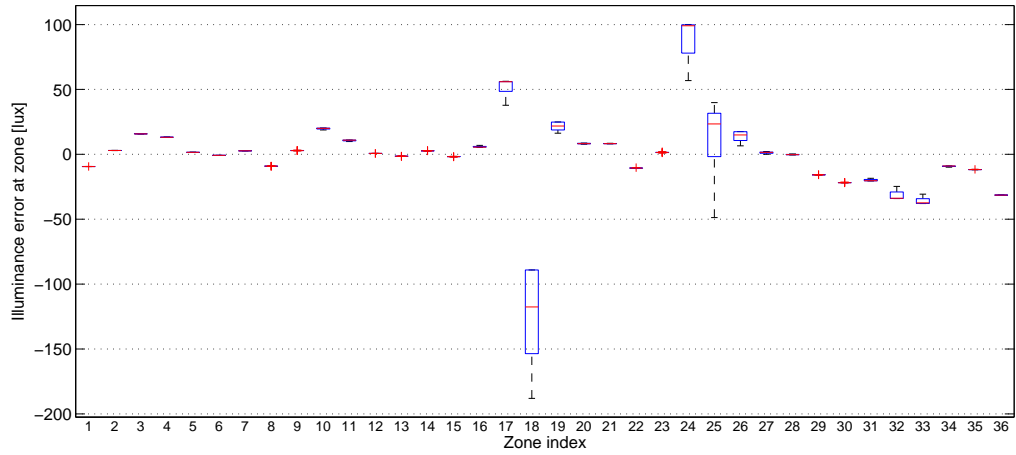


Fig. 4.26 Illuminance error at each zone with the reference stand-alone controller, minimum approach (1000 simulations).

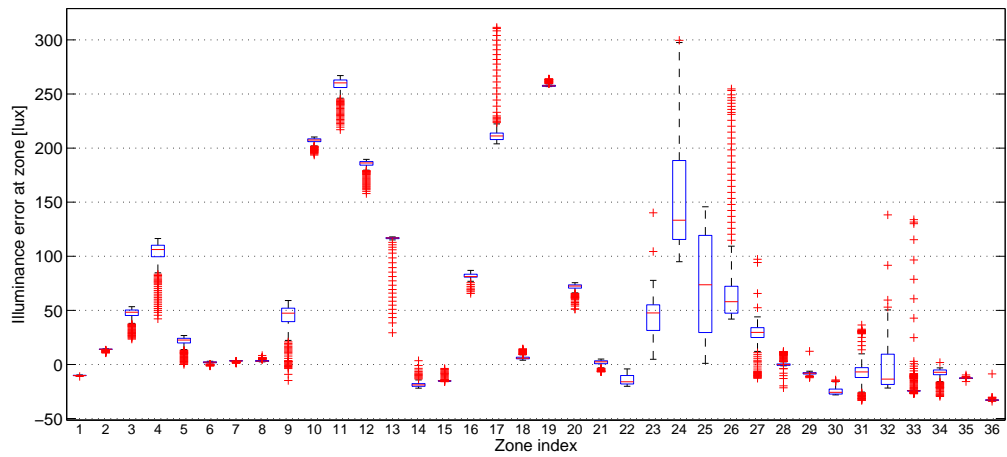


Fig. 4.27 Illuminance error at each zone with the proposed controller, minimum approach (1000 simulations).



# Chapter 5

## Conclusions and future works

In this thesis a lighting system of multiple luminaires, with co-located light and occupancy sensors, is considered for daylight and occupancy adaptation. A multi-variable feedback controller to perform personal control has been presented. Methods for specifying the light sensor set-points were considered to account for user illumination personal control requests. The centralized controller was designed by minimizing a cost function, constituted by a weighted sum of squares of the illumination error and square of the power consumption, with illumination constraints at the light sensors and physical constraints on luminaire dimming levels. Two approaches have been used to minimize this cost function: an unconstrained optimization and a constrained optimization. The performance of the proposed methods was evaluated via simulations and compared with a benchmark stand-alone controller in an open plan office lighting model. The unconstrained optimization led to a significant energy consumption due to saturation of certain luminaires affected by huge daylight contribution. On the other hand, as compared to the reference controller, the proposed constrained optimization was found to have lesser under-illumination while achieving similar energy savings under different daylight conditions in the sensor-driven control scenario. Moreover this method has better performance even in terms of achieving the reference set-points in the sensor-driven personal control scenario. Finally, the constrained approach also has better transient behaviour, showing smaller settling time and a significant reduction in overshoot.

The scope of this thesis was the design of personal control algorithms and performance evaluation via simulations. Future works may be related to:

- **User satisfaction:** it might be interesting and useful to study the influence of various control system parameters as well as system performance indicators from a user experience perspective. These topics should be studied in future and validated with user field tests in office lighting settings.
- **Wireless technology:** wired networks will be slowly replaced by wireless networks to overcome many issues, such as enhanced control, savings in cabling cost and easier installation. Thus wireless communication is a promising approach, easier to deploy in comparison to a wired system. On the other hand, wireless networks suffer from unreliable communications leading to high packet-loss rates and large random delays due to interferences, power failures, multipath fading. An accurate work should thus be done studying the effect of these packet losses on the proposed controller, as was done in [24] for the stand-alone controller used as a benchmark in this work.
- **Mapping from sensors to workstations:** another challenge is to find a suitable map that relates the measured illuminance at the light sensors with the illuminance at the workstation. In this way it shall be possible to control the illuminance at zones directly while leaving the light sensors still at the ceiling.

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# Appendix A

## TrueTime Toolbox

During the entire period of this thesis the Truetime toolbox [22] has been used. TrueTime is a Matlab/Simulink-based simulator for real-time control systems. It facilitates co-simulation of controller task execution in real-time kernels, network transmissions, and continuous plant dynamics. It includes several features, such as:

- Written in C++ MEX, event-based simulation,
- External interrupts,
- Possibility to write tasks as M-files or C++ functions. It is also possible to call Simulink block diagrams from within the code functions
- Network block (Ethernet, CAN, TDMA, FDMA, Round Robin, Switched Ethernet, FlexRay and PROFINET)
- Wireless network block (802.11b WLAN and 802.15.4 ZigBee)
- Battery-powered devices, Dynamic Voltage Scaling, and local clocks
- Stand-alone network interface blocks

TrueTime was developed mainly by Martin Hast, Martin Ohlin, Dan Henriksson, Anton Cervin and Johan Eker from Lund University in Lund, Sweden. All the networks, communication systems and simulation were run employing TrueTime. Many parameters are tunable in each communication system; though this appendix a short description will be given and the most used parameters will be briefly described.

## A.1 Wired network description and parameters

In Simulink the TrueTime network block is available. This block simulates medium access and packet transmission in a local area network. When a node tries to transmit a message (using the primitive *ttSendMsg*), a triggering signal is sent to the network block on the corresponding input channel. When the simulated transmission of the message is finished, the network block sends a new triggering signal on the output channel corresponding to the receiving node. The transmitted message is put in a buffer at the receiving computer node. A message contains information about the sending and the receiving computer node, arbitrary user data (typically measurement signals or control signals), the length of the message, and optional real-time attributes such as a priority or a deadline.

Six simple models of networks are supported: CSMA/CD (e.g. Ethernet), CSMA/AMP (e.g. CAN), Round Robin (e.g. Token Bus), FDMA, TDMA (e.g. TTP), and Switched Ethernet. The propagation delay is ignored, since it is typically very small in a local area network. Only packet-level simulation is supported—it is assumed that higher protocol levels in the kernel nodes have divided long messages into packets, etc.

The network block is configured through the block mask dialogue shown in Figure A.1. Using the command *ttSetNetworkParameter*, it is also possible to change some parameters on a per node basis. The following network parameters are instead common to all models:

- **Network number:** The number of the network block. The networks must be numbered from 1 and upwards. Wired and wireless networks are not allowed to use the same number,
- **Number of nodes:** The number of nodes that are connected to the network,
- **Data rate (bit/s):** The speed of the network,
- **Minimum frame size (bits):** A message or frame shorter than this will be padded to give the minimum length. It denotes the minimum frame size, including any overhead introduced by the protocol,
- **Loss probability (0-1):** The probability that a network message is lost during transmission. Lost messages will consume network bandwidth, but will never



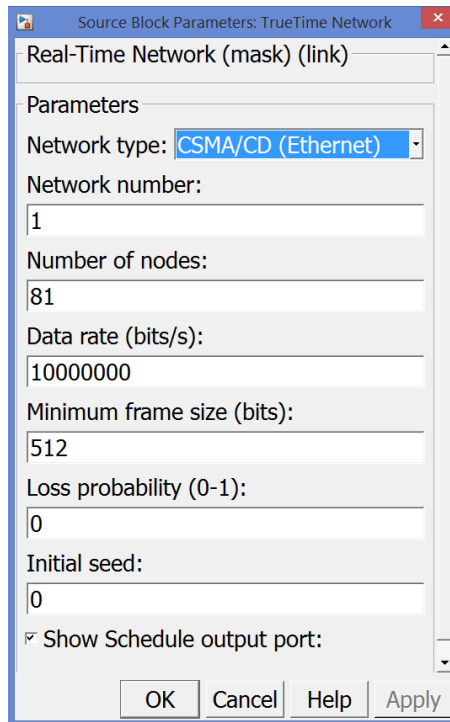


Fig. A.1 The dialogue of the TrueTime network block.

arrive at the destination. In this work the communication has always been supposed reliable and without delays, so the loss probability has been set to zero,

- **Initial seed:** The starting seed for the random number generator used to evaluate the loss probability.





