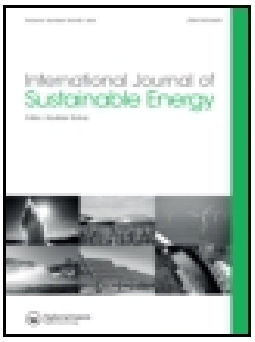

International Journal of Sustainable Energy

ISSN: 1478-6451 (Print) 1478-646X (Online) Journal homepage: http://www.tandfonline.com/loi/gsol20

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To cite this article: Sotiris Papantoniou, Denia Kolokotsa, Kostas Kalaitzakis, Davide Nardi Cesarini, Eduard Cubi & Cristina Cristalli (2014): Adaptive lighting controllers using smart sensors, International Journal of Sustainable Energy, DOI: 10.1080/14786451.2014.923887

To link to this article: http://dx.doi.org/10.1080/14786451.2014.923887

International Journal of Sustainable Energy, 2014
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Adaptive lighting controllers using smart sensors

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(*Received 27 November 2013; final version received 7 May 2014*)

The aim of this paper is to present an advanced controller for artificial lights evaluated in several rooms in two European Hospitals located in Chania, Greece and Ancona, Italy. Fuzzy techniques have been used for the architecture of the controller. The energy efficiency of the controllers has been calculated by running the controller coupled with validated models of the RADIANCE back-wards ray tracing software. The input of the controller is the difference between the current illuminance value and the desired one, while the output is the change of the light level that should be applied in the artificial lights. Simulation results indicate significant energy saving potentials. Energy saving potential is calculated from the comparison of the current use of the artificial lights by the users and the proposed one. All simulation work has been conducted using Matlab and RADIANCE environment.

Keywords: fuzzy control; artificial lights; energy consumption; Radiance software

Introduction

Environmental, economic and policy reasons mandate the reduction of the energy consumption of buildings. The increase in atmospheric CO_2 concentration, the elimination of fossil fuels and the stability of the energy grids are among the causes leading to the reduction of energy consumption in the building sector. Energy consumption of buildings is measured at 40% of worldwide energy consumption (Pérez-Lombard, Ortiz, and Pout 2008).

Energy savings in buildings can be achieved using either passive or active energy- saving techniques. Passive energy-saving techniques, such as wall/ roof insulation or fenestrations with low-e glass and window frames with low *U*-value contribute significantly to the reduction of energy consumption for heating and cooling. Although passive energy saving techniques reduce energy losses from the fabric of the buildings, energy consumption can also be reduced by adjusting the internal gains, which directly affect electricity consumption. Moreover, during the summer period, when cooling is most required, the surplus internal gains increase indoor temperature, which is directly related to the cooling loads.

Among the most common internal gains existing in buildings is the usage of artificial lights. Artificial lights in buildings used for offices consume a significant amount of energy worldwide

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Table 1. Luminous efficiency of different types of light, based on EN 12464.1 2002: 'European Standard for Interior Lighting'.

Type of light	Luminous efficiency (lm/W)
Incandescent	10–18
Halogen	15–25
Compact fluorescent	50–60
Linear fluorescent	50–60
LED	30–60

compared to the total building's energy consumption as presented by Santamouris et al. (1994) and Lam, Li, and Cheung (2003), affecting the cooling loads of buildings as reported by Franzetti, Fraisse, and Achard (2004). According to Santamouris research, artificial lights consume 10% of total energy consumption based on measurements in the buildings of Greece.

Current artificial light systems use fluorescent lamps. Before the mandatory installation of fluorescent light bulbs around Europe (Commission 2009), most buildings had incandescent light bulbs which were very inefficient. Lately, LED luminaire with proper driving circuitry adjust indoor illuminance to comfort levels. The adjustment of illuminance to the minimum required level compared to the maximum capacity of the light fixtures generates energy saving potential. The efficacy of each pre-mentioned system can be seen in Table 1.

The efficiency of such energy saving techniques is also affected by the behaviour of occupants inside the buildings which may reduce the energy saving potential. On the other hand, new systems such as smart controllers can adjust the artificial light level based on data collected from illuminance sensors and occupancy detectors. A smart controller can also be adjusted to the needs of the occupants if during the pre-commissioning period the manual-control of the occupants has been measured and analysed as presented by Reinhart (2001), Reinhart and Voss (2003).

Nevertheless, when designing smart controllers for optimum and energy efficient operation of the building services, the existence of an advanced and integrated simulation environment is very important.

To this end, the aim of the present work is to present a methodology for developing and testing a smart fuzzy controller for the efficient operation of artificial lights. The smart controllers developed in Matlab are connected with the Radiance simulation models. The overall approach is tested using the data extracted by two hospitals. The paper is organised in five sections. Section 2 includes the available control techniques for artificial light systems. Section 3 incorporates the fuzzy-based controller and the set parameters, while Section 4 presents the selected hospitals, the development of the Radiance model, its validation process and the energy consumption a priori and a posteriori the implementation of the fuzzy controller. Finally, Section 5 incorporates the conclusions and propose issues for future research.

Available control techniques for energy savings of artificial light systems

The issue of energy savings from artificial lights, maximising the benefits from natural daylight, has been raised by many researchers. The initially developed controllers switched artificial lights on/off based on the indoor illuminance level (Knight 1998). As Knight mentioned in his research, the 'Mark 1' model could only adjust the illuminance set-point at 500 lux, forbidding the user from setting a different set-point based on the usage of each workstation.

The communication between sensors and actuators can be wired or wireless. An example of a wireless on/off controller is designed and applied by Nippun Kumaar, Kiran, and Sudarshan

(2010) saving 14.4 kWh per month, which is 20% of the energy consumption of the artificial lights. In this installation, wireless sensors located in the various areas of a room switch artificial lights on/off sending the signals to a wireless actuator located next to the light fixture.

Apart from on/off systems, more sophisticated controllers can be used, especially for light systems that integrate dimmers. A wireless control system was designed and tested by Wen and Agogino (2010). According to their research if a photo sensor and a controller are located above each workstation, energy savings can be up to 60.8% considering a specific occupancy profile for an office, comparing to the initial state where all the lights were switched on/off simultaneously. The advantage of this control system compared to the previous one is the capability to dim artificial lights separately. Another comparison between automated on/off systems and fully dimmable systems has been presented by Frattari, Chiognm, and Boer (2009). According to their research, a fully dimmable system can save up to 68%, during autumn and up to 43% during winter, while an automated on/off system saves 56% and 20%, respectively. Dimmable controllers have also been available in the market and have been tested to measure their energy savings. Knight (1998) has tested two products available in the market and has found that a controller with more dimming capabilities can save more energy even during the night since it can adjust the provided illuminance to the required set-point.

Lighting controllers can be combined with other daylight harvesting techniques such as light shelves. Raphael (2011) developed a control which combines the movement of light-shelves with proper dimming of artificial lights, improving the performance of the system and saving 12% comparing to a steady light-fixture.

Furthermore, automated control of light fixtures can be combined with other parameters such as indoor air quality and thermal comfort to achieve an overall optimisation of the building's energy consumption while guarantying indoor conditions inside buildings as described by Dounis et al. (2011) based on simulation results and Kolokotsa et al. (2009) based on real measurements. Another approach for artificial lights control is presented by Kurian et al. (2008) combining the control of the artificial lights with a separate control of the venetian blinds in order to maximise daylight harvesting and minimise visualisation problems. Based on the research, energy saving potential depending on the orientation of the windows and the floor level varies from 21% to 60%. The development of the fuzzy control for dimming the artificial lights has been presented by Kurian et al. (2005) and its application including the achieved results has also been published by Colaco et al. (2012) Although fuzzy technology has been developed since 1965, their application is continuously increasing. Their main advantage is the users' knowledge inserted in the controller in the form of rules. Another advantage of fuzzy technology is its adaptability to actual measurements using ANFIS (Adaptive Neuro Fuzzy Inference System) (Jang 1993) architecture, in which the fuzzification and de-fuzzification parameters are updated based on measurements collected on-site.

An automated controller can also be combined with a fault detection system in order to inform the energy managers that a sensor might send some fault measurements. Such a fault detection system has been developed by Kolokotsa, Pouliezos, and Stavrakakis (2005) showing remarkable results despite its simplicity.

Fuzzy controller analysis

The fuzzy controller, developed for the artificial light systems, is based on the 'Sugeno' type fuzzy model. It is coupled with models validated with real-time data running annual simulation in order to test its efficiency. In case the performance of the controller coupled with the model is not as expected, the fuzzification and de-fuzzification parameters are tuned properly.

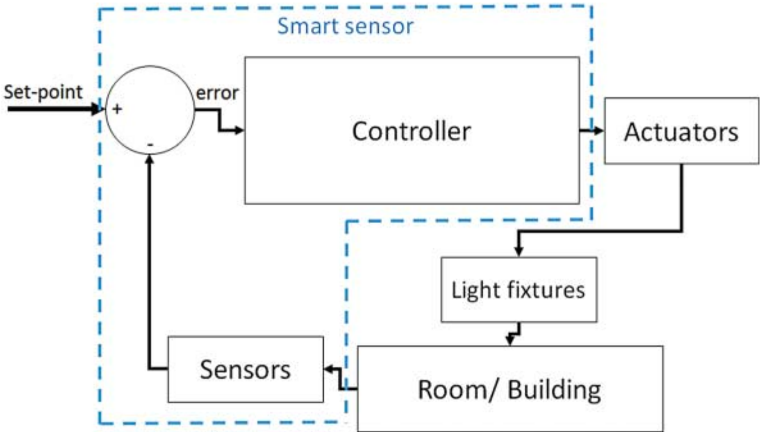

Figure 1. Architecture of the smart sensor applied in a building/room for controlling artificial lights.

Table 2. Architecture of the fuzzy controller.

Type of fuzzy controller	Sugeno	
No. of inputs	1: Error between current and desired light level	
No. of outputs	1: Change in the artificial lights state	
Fuzzification membership functions	5	
Fuzzification parameters (trapmf)	NE	[−1000 – 200 – 150 – 50]
	ZE	[−50 – 252550]
	PO	[150 200 2000 2800]
	SNE	[−150 – 75 – 250]
	SPO	[20 50 100 200]
De-fuzzification parameters (constant)	NE	[−1]
	SNE	[−0.3]
	ZE	[0]
	SPO	[0.3]
	PO	[1]
User's knowledge	1, 5 (1): 1	4, 4 (1): 1
	2, 3 (1): 1	5, 2 (1): 1
	3, 1 (1): 1	
Further fuzzy parameters	AndMethod: 'prod'	OrMethod: 'probor'
	ImpMethod: 'prod'	AggMethod: 'sum'
	DefuzzMethod: 'wtaver'	

Notes: NE, negative; ZE, zero; PO, positive; SNE, small negative; SPO, small positive.

The architecture of the controller as part of a smart sensor can be seen in Figure 1. As can be seen, the controller can be embedded into a smart sensor which senses the conditions in the room, and sends the signals to the actuators. The sensors integrated in the smart sensor are an indoor illuminance sensor and a presence indicator. When presence is detected, the controller estimates the required change of the artificial light level, and the new state in order to meet the users' requirements. When users are not detected inside the room, lights will be either switched off or dim further in order to maximise energy savings. The architecture of the controller can be seen in Table 2. The fuzzification and de-fuzzification parameters are tuned based on the performance of the fuzzy controller coupled to the Radiance model. The membership function for the fuzzification of input can be seen in Figure 2.

The user's knowledge is included in the form of rules:

If input is NE **then** output is PO

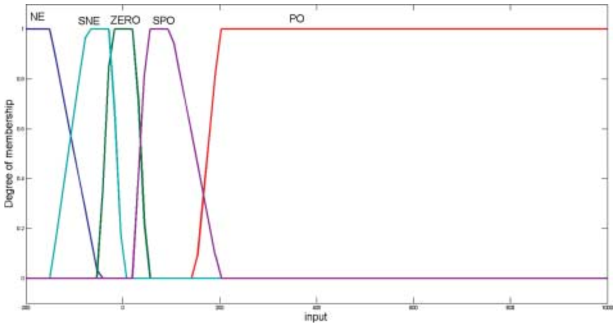

Figure 2. Membership functions for the fuzzification of input value.

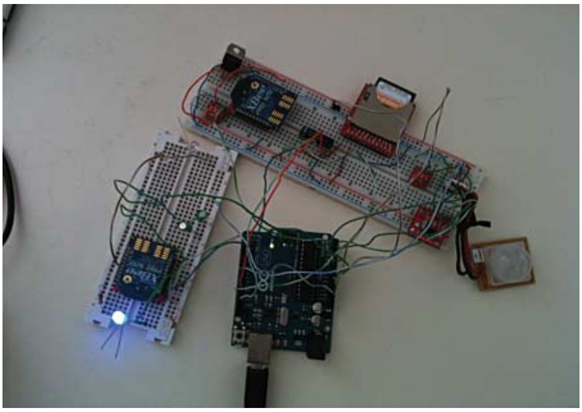

Figure 3. A smart sensor developed in the framework of Green@Hospital project.

If input is PO **then** output is NE
If input is ZE **then** output is ZE
If input is SNE **then** output is SPO
If input is SPO **then** output is SNE

The controller presented above is the software part of a smart sensor that runs from a central computer based building management system and sends commands to the actuators. Alternatively, the fuzzy controller can be embedded to a microprocessor to run autonomously and distributed, as presented by Foutrakis et al. (2013) and can be seen in Figure 3.

Furthermore, the controller can be applied in any room of a specific building.

Application of the controller in different light systems

The controller can be applied in artificial light systems with dimming capabilities and in on/off systems as long as more than one light fixture with different circuits is installed.

In case of systems with dimming possibilities, the output of the controller should be confined to the limits of the dimming device (ex. 10% step of dimming, linear) and then it has to be filtered (minimum and maximum dimming values) in order to meet the requirements of the dimming system.

In case of using on/off systems with different light fixtures systems, a different approach is required in which lights are switched on or off properly. The controller initially switches on the

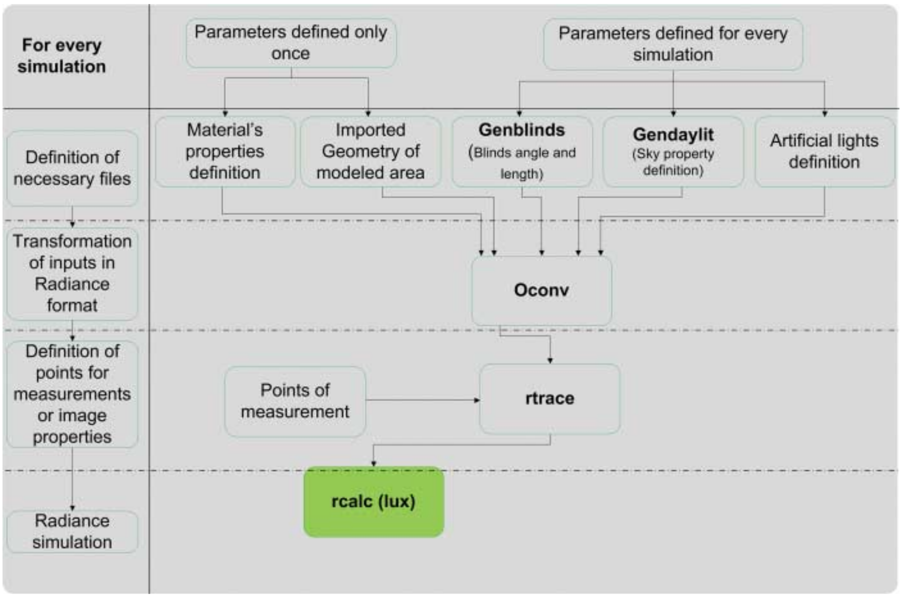

Figure 4. Steps of the radiance simulation to simulate illuminance level is specific point.

light fixtures closer to the entrance of the room, and if the light level is not sufficient, the light fixture close to the window is activated as well. Thus, daylight level is used as much as possible, since the daylight factor's value is higher close to the window comparing its value close to the entrance of the room (Li, Cheung, and Lau 2006). The output of the fuzzy controller has to interpreted by the on/off system. The logic implied can be seen in the equation below. The values of 'fuzzy_output' in the equation are selected by tuning the controller, considering that two light fixtures are available per room and they are separately controlled.

```
If fuzzy_output $>0.75$ then
    Switch 2 more light fixtures on
elseif fuzzy_output $>0.25$ then
    Switch 1 more light fixture on
elseif fuzzy_output $> -0.25$ then
    Do not change lights' state
elseif fuzzy_output $> -0.75$ then
    Switch 1 more light fixture off
else
    Switch 2 more light fixtures off
end
```

Since the fuzzy controller is developed using Matlab and the rooms light simulation is performed using RADIANCE, an interconnection between MATLAB and Radiance was considered necessary. Radiance software (version 4 in Windows OS) is a combination of several sub-programs running in a disk operating system (DOS)/Linux environment (Ward and Shakespeare 1998). Matlab software calls each sub-program separately using a 'dos' built in function. The sub-programs required to simulate the illuminance level in a point using Radiance software are illustrated in Figure 4.

Simulation of the illuminance level in a specific point using Radiance software is performed calling the 'rtrace' sub-program. 'rtrace' command requires a specific type of file which is produced

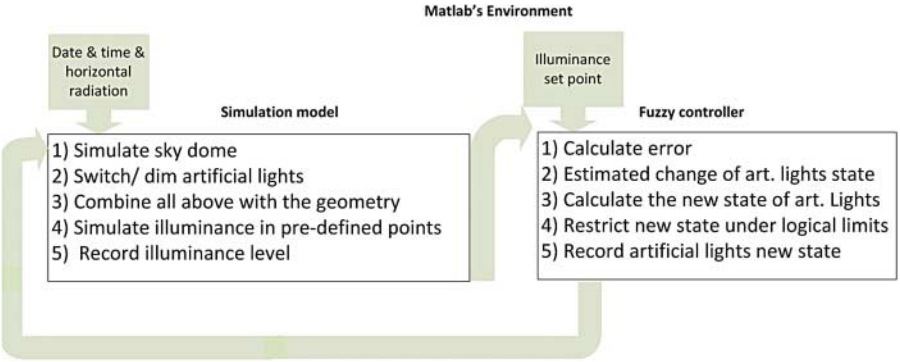

Figure 5. Workflow of the connection between radiance software and fuzzy controller developed in Matlab's environment.

using the 'oconv' command. Geometry of a room, material, and sky properties are converted in a format that Radiance software uses to estimate the illuminance level or develop photorealistic images. Outdoor illuminance is simulated using the 'gandaylit' or 'gensky' sub-program.

The state of the lights is also saved in order to estimate the consumption and savings for the simulation period. The output of the Matlab script is the illuminance level in the pre-selected points of the model. The connection between Matlab and software Radiance can be seen in Figure 5.

Case studies

The aforementioned controller is applied in two hospitals located in Ancona, Italy and Chania, Greece. An estimation of the energy saving potential is done by running the controller with validated lighting models developed in Radiance.

The validation process has been conducted using indoor illuminance measurements collected from the selected rooms and compared with simulation results of illuminance in the same points of the rooms.

Hospital of Chania – paediatric department

The hospital of Chania is located in Crete, Greece. The selected department is located in the third floor and three rooms are selected, two of which face North-East and the last one faces South-West (SW). In the framework of the European Project: 'Green@Hospital', measurements (illuminance and concerned lighting conditions) are collected from the 17th of May 2013. A Radiance model is developed for each room for estimating the illuminance level.

Preliminary analysis of lighting measurements indicates that energy savings are possible if a lighting controller is applied. The estimation of energy saving is performed by measuring the time when the lights were switched on and no occupants were in the room or the illuminance level is above the minimum required. Numerical estimations from the energy savings concerning the selected rooms, for the measuring period, are presented in Table 3.

Development of the simulation model in the paediatric department of the hospital of Chania

A 3D model of the hospital of Chania has been developed (Figure 6) based on floor plans and sections provided in electronic form by the hospital, enhancing the geometric details in the paediatric

Table 3. Energy saving potential in artificial lights, hospital of Chania.

Ward	Room id	Room	Measured energy consumption [kWh]	Savings due to Presence detection	Savings due to Set-point	Combined savings
Paediatric	1	Patients' room	8.9	65.7%	25%	72.60%
	2	Doctors' room	49.4	82.17%	21.95%	88.39%
	3	Doctors' rest room	12.88	99.65%	0.0%	99.65%

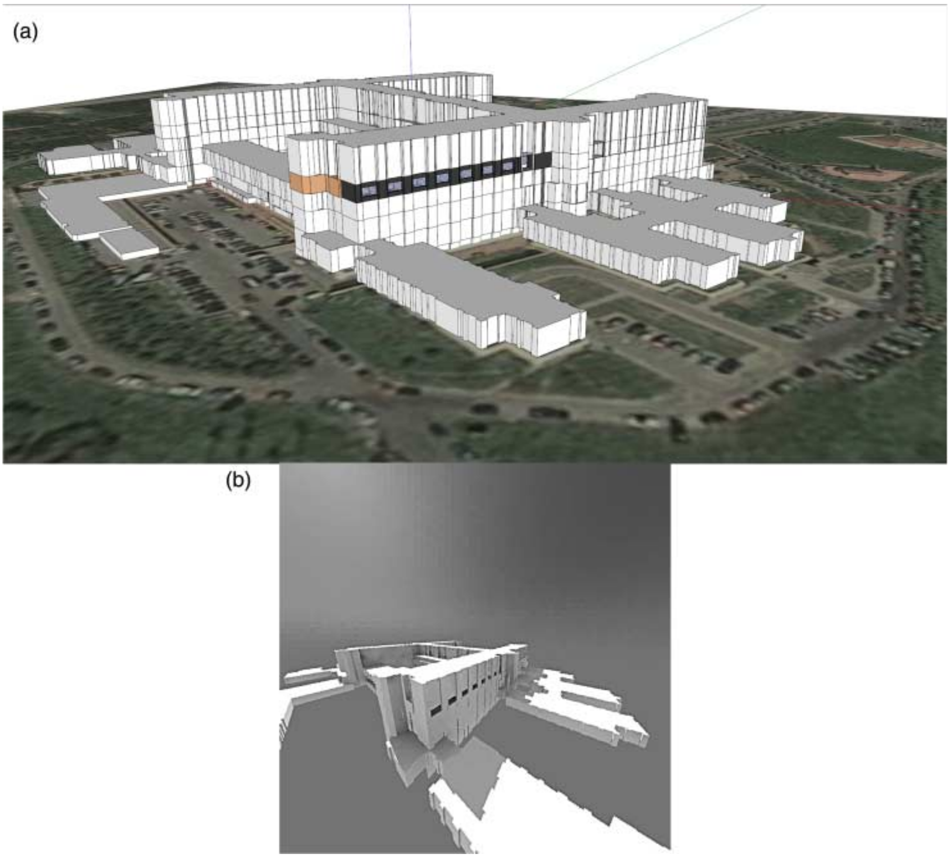

Figure 6. SketchUp model and the respective one in radiance for the hospital of Chania.

department. In Figure 7, Doctors' office can be seen in the hospital of Chania. In the top left corner of the figure, the illuminance and occupancy sensor can be seen. The installed equipment in each room for measuring the illuminance level, occupancy, energy consumption and controlling the artificial lights is presented in Table 4.

The validity of the Radiance model to estimate accurately indoor illuminance levels has been verified comparing measured illuminance values and simulated ones for the period between 29th till the 31st of July 2013. The statistical comparison between measured and simulated illuminance values is done comparing the same time-series for the selected rooms. The measured values have been taken from the sensors permanently located in the selected rooms, while the simulated values have been estimated using the Radiance software. Measured and

Figure 7. Doctors room in paediatric department in the hospital of Chania.

Table 4. Installed equipment in each selected room in paediatric department, hospital of Chania.

Equipment	Parameter
Thermokolon – MDS Standard 1	Illuminance level
	Occupancy indication
FX07 – Field controller	Art. lights actuator
Kamstrup 382 generation L	Energy meter

simulated illuminance values for patients' room can be seen in Figure 8. X-axis indicates the time-stamp of the indoor illuminance measurements, plotted in Y-axis collected from the rooms every 1 h using permanently installed equipment in specific points and stored in the local building management system. For the rest of the rooms, the comparison is presented in Table 5 using the pre-mentioned comparison. Outdoor horizontal radiation was measured at the Technical University of Crete 7.5 km from the hospital of Chania. The technical characteristics of the light fixtures have been developed using Software Relux (Relux Informatik AG 2012). The artificial light system in the hospital is based on switching the lights on/off.

Comparing the values from the statistical point for the three-day period, the R^2 values for the three selected rooms can be seen in Table 5. The low R^2 values in the Doctors' rest room can be justified by the fact that doctors have been using a dark-coloured curtain at will to reduce daylight and the overheating effects of direct sunlight, since the orientation of the room is SW.

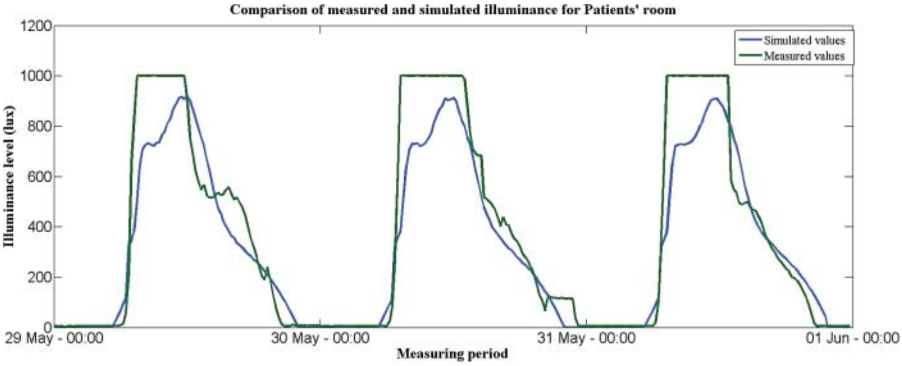

Figure 8. Comparison of measured and simulated illuminance level in selected point in the patients' room.

Table 5. Statistical comparison of measured and simulated values for lighting in hospital of Chania.

Department	Room	R^2
Paediatric	Patients' room	0.9095
	Doctors' room	0.7762
	Doctors' rest room	0.2949

Application of the fuzzy controller in the hospital of Chania

In the three selected rooms, the controller will be used, controlling two light fixtures which are operated using different switches. For each room, the controller selects which fixture will operate based on an illuminance sensor and presence detection measurement *in situ*. The selection is made by comparing the input from the sensor and the desired set-point for each room. For the selected rooms in the hospital of Chania, the required set-point can be seen in Table 3. In Figure 9, the indoor illuminance level can be seen under three different operations for three continuous days during summer and in Figure 10 for three continuous days during winter. As can be seen in both Figures 9 and 10, the operation of the light fixtures using the fuzzy controller saves energy by switching the one light fixture off since the illuminance level using only one is sufficient. Moreover, since there is a specific schedule for the operation of the specific room (10:00–14:00 is occupied), the controller will switch the lights off in case of no presence faster (after 5 min) when is not occupied compared to when it is occupied (after 15 min). The effect of the pre-mentioned control cannot be modelled using Radiance since there are no measurements of presence detection with a time-step of 5 min or less. Energy saving potential and illuminance comfort can also be increased by running the controller within a shorter time period for example every quarter.

Energy consumption of the artificial lights a priori and a posteriori, the fuzzy controller implementation for a specific period is calculated from the operative hours of the artificial lights during this period multiplied by their maximum power demand. Baseline consumption of the light fixtures for 1 year is calculated at 67.5 kWh considering as baseline consumption operation of both artificial lights when the room is scheduled to be occupied (10:00–14:00) and an illuminance level below 500 lux. Performing an annual simulation of the Radiance model coupled with the controller developed in Matlab, the energy saving potential for the doctors' room has been estimated at 58%.

Hospital of Ancona – oncology and haematology department

The selected departments are located in the second floor of the hospital. In these departments, 10 rooms in total have been selected (7 from the oncology department and 3 in the haematology one).

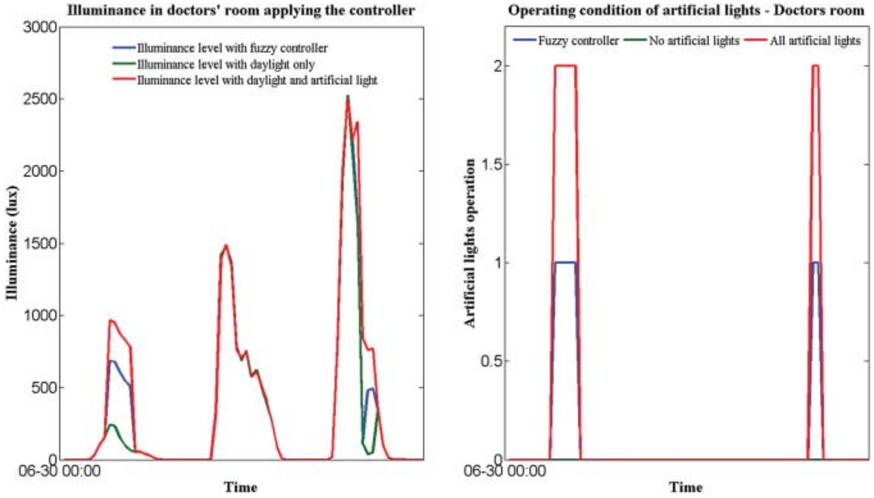

Figure 9. Indoor illuminance level in the doctors' room hospital of Chania under different artificial lights conditions, during summer period.

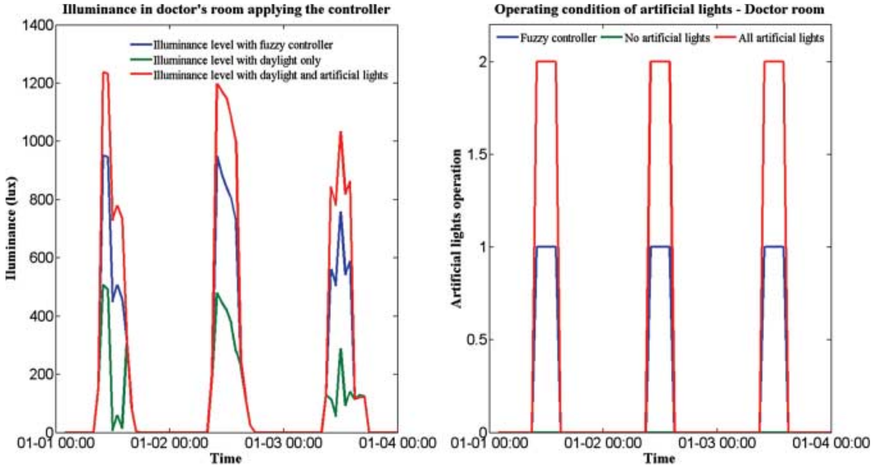

Figure 10. Indoor illuminance level in the doctors' room hospital of Chania under different artificial lights conditions, during winter period.

The installed equipment for measuring illuminance level, occupancy and energy consumption can be seen in Table 6. One passive infrared sensor with an integrated illuminance sensor (UP 258E21) is installed in each room's ceiling at 3.0 m height and covers an area of 6.5 m × 3.7 m. The sensor is located in the centre of the ceiling to cover the whole room. The control of artificial lights is zone based. Similar to the hospital of Chania, measurements have been collected for the selected rooms during the time period between November 2012 and January 2013, collecting data for 1 week per selected room. Measured energy consumption (kWh), as well as energy saving potential for a representative day of the week for each room, is presented in Table 7.

Energy saving potential is estimated considering as waste of energy the operation of artificial lights when the rooms are not occupied or when the indoor illuminance level exceeds the minimum required as described in Table 8. In order to identify if these savings can be achieved using the

Table 6. Installed equipment in each selected room in the hospital of Ancona.

Equipment	Measured parameter
UP 258E21: Presence detector with brightness sensor	Illuminance level Occupancy indication
KL3403|3-phase power measurement terminal	Energy meter

Table 7. Measured energy consumption and energy saving potential in artificial lights, hospital of Ancona.

Ward	Room id	Room	Measured energy consumption [kWh]	Savings due to: Presence detection	Savings due to: Dimming	Combined savings
Haematology	1	Warehouse	2.1	55%	16%	62%
	2	Nurse office	3.7	34%	16%	44%
	3	Doctors office	2.35	35%	53%	70%
Oncology	4	Visitors waiting room	5.18	39%		39%
	5	Nurse office	2.45	7%	50%	54%
	6	Archives (two rooms)	NA	NA		
	7	Ambulatory	0.5	18%	21%	35%
	8	Patients waiting room	2.6	36%	35%	58%
	9	Day hospital room	NA	NA		

Table 8. Required illuminance set-points for selected rooms in the hospitals of Chania and Ancona based on EN 12464.1 2002: ‘European Standard for Interior Lighting’.

Hospital of Chania	Patients’ room	100 lux
	Doctors’ office	500 lux
	Doctors’ rest room	500 lux
Hospital of Ancona	Warehouse (haematology department)	200 lux
	Nurses’ office (haematology departent)	500 lux
	Doctors’ office (haematology department)	500 lux
	Visitors waiting room (oncology department)	200 lux
	Archives – two rooms (oncology department)	200 lux
	Ambulatory (oncology department)	500 lux
	Nurse room (oncology department)	500 lux

developed fuzzy controller, a Radiance model of the hospital has been developed and the controller has been tested running an annual simulation.

Development of the simulation model in the oncology and haematology department of the hospital of Ancona

The developed 3D model in SketchUp and the Radiance lighting model can be seen in Figure 11(a) and 11(b). Moreover in Figure 12, a simulated image from Radiance software can be seen, presenting illuminance values in the internal surfaces of the nurses’ room under daylight and artificial light. The visitors’ waiting room with the installed equipment for monitoring illuminance level and occupancy can be seen in Figure 13. The validation results for the visitors’ waiting room in the oncology department can be seen in Figure 14, while for the rest of the rooms, the correlation between measured and simulated values can be seen in Table 9.

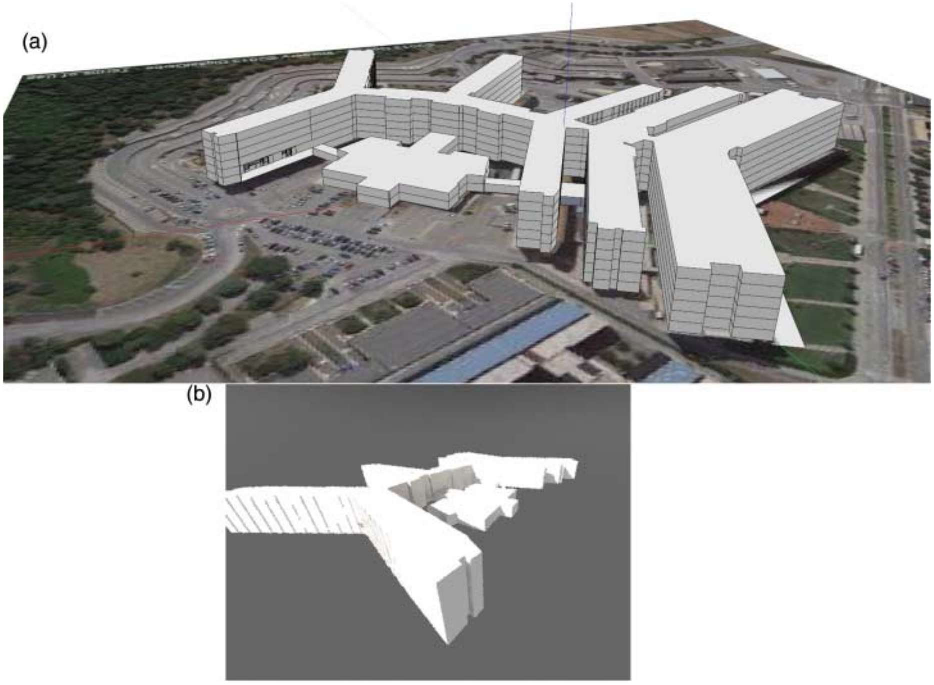

Figure 11. SketchUp model and the respective one in radiance for the hospital of Ancona.

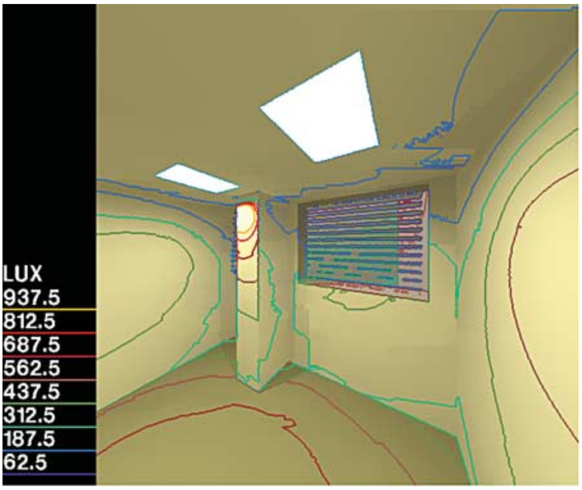

Figure 12. Visualisation of the nurses' room – haematology department using radiance.

The statistical values of the specific rooms can be considered accurate taking under consideration that measurements have been collected during the winter when many clouds affect the indoor illuminance. Moreover, indoor illuminance is affected by the occupants' behaviour inside the rooms. Finally for the rooms located in the oncology department, we had very little information related to the operation of the venetian blinds.

In the hospital of Ancona, the artificial lights will dim based on the decisions of the fuzzy controller and presence indication. Outdoor horizontal radiation data are collected from Loccioni Group head-quarters which are located only few kilometres from the hospital of Ancona.

Figure 13. Visitors waiting room, oncology department, hospital of Ancona.

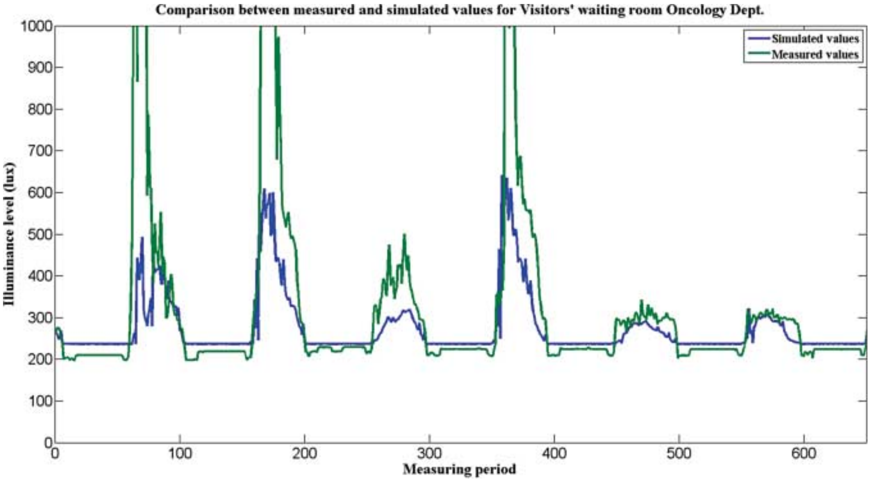

Figure 14. Comparison of measured and simulated illuminance level in selected point in the oncology department, patients' waiting room.

Table 9. Statistical comparison of measured and simulated values for lighting in hospital of Ancona.

Department	Room	R^2
Haematology	Warehouse	0.7874
	Nurse office	0.8332
	Doctors office	0.9447
Oncology	Visitors waiting room	0.3474
	Nurse office	0.6294
	Archives (two rooms)	0.4439
	Ambulatory	0.2540
	Patients waiting room	0.2620
	Day hospital room	0.3953

Application of the fuzzy controller in the hospital of Ancona

Similarly to the hospital of Chania, the hospital of Ancona has specific set-points for the selected rooms, which can be seen in Table 8 and a schedule for each room having different required illuminance level for every different schedule which can be seen in Table 10. The application of the fuzzy controller for 2 days during spring and 3 days during winter in the warehouse of the haematology department can be seen in seen in Figures 15 and 16 where the illuminance level inside the room can be seen under three different conditions. On the right side of Figures 15 and 16, the lights' operating level can be seen. From the dimming level of the artificial lights, the energy consumption of the artificial lights can be estimated as a relation between the dimming level and the maximum consumption when lights are operating under maximum power. Analysing the dimming level of the figures, it can be seen that the artificial lights are working mostly at 75% of their maximum paper keeping the light level stable around the desired set-point (200 lux), saving energy assuring the indoor level. Savings can be increased if the controller is applied more frequently (ex. 10 min).

An annual simulation has been performed combining the controller developed in Matlab and the RADIANCE developed model of the hospital of Ancona. A representative presence schedule has been established for the selected rooms to provide the necessary inputs to the controller. The presence schedule and the necessary set-points for the selected rooms are presented in Table 10.

Table 10. Provided parameters for the annual simulation.

Selected rooms of hospital of Ancona	Time	Presence indication	Light set-point
Visitors waiting room (Room 7)	00:00–01:59	1	200 lux
	02:00–05:59	0	50 lux
	06:00–20:59	1	200 lux
	21:00–21:59	0	50 lux
	22:00–23:59	1	200 lux
All other simulated rooms in oncology and haematology departments	00:00–06:59	0	0 lux
	07:00–18:59	1	500 lux
	19:00–23:59	0	0 lux

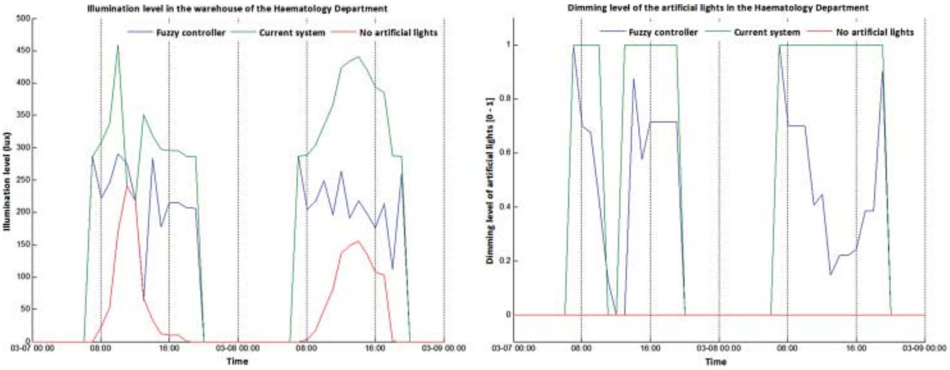

Figure 15. Indoor illuminance level in the warehouse, haematology department, hospital of Ancona under different artificial lights conditions, during spring period.

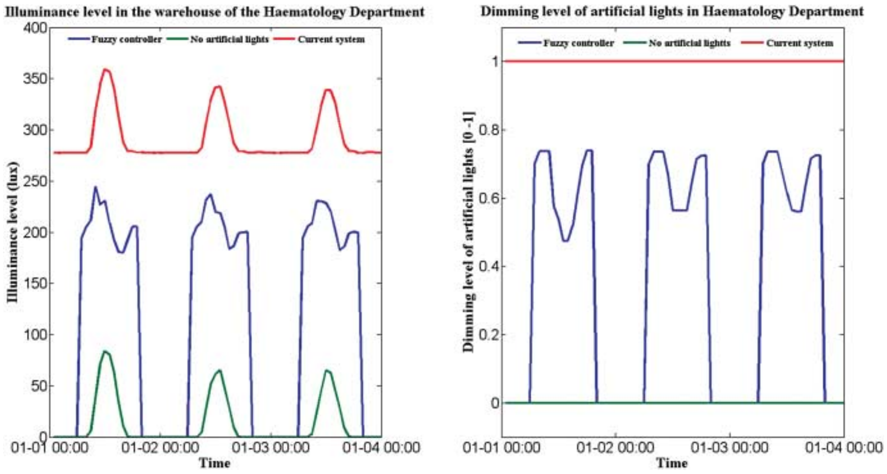

Figure 16. Indoor illuminance level in the warehouse, haematology department, hospital of Ancona under different artificial lights conditions, during winter period.

Table 11. Estimated energy savings from the annual simulation.

Selected rooms of hospital of Ancona	Annual baseline consumption [kWh]	Estimated energy savings
Visitors waiting room (oncology department)	1244.7	36%
Nurse office (haematology department)	1030.7	54%
Doctors office (haematology department)	1550.6	45%
Warehouse (haematology department)	639.2	53.1%
Archives – two rooms (oncology department)	319.2	29%
Ambulatory (oncology department)	259.4	11%
Nurse room (oncology department)	294.9	17.6

Running the simulation, the following energy savings are estimated based on the state of the artificial lights. The results from the simulation can be seen in Table 11.

Comparing Tables 7 and 11, it can be seen that the estimation of possible energy savings due to dimming is similar for the visitors' waiting room. For the other two rooms located in the haematology department, the simulation shows that the savings are much higher compared to the initial estimation. This difference is reasonable if we assume that the initial estimations have been calculated using measurements collected during the winter. The rooms are self-shaded by hospital and thus daylight is much lower compared to the summer.

Conclusions and future prospects

In this paper, a fuzzy controller has been developed for controlling artificial lights. The fuzzy controller can be applied to dimmable and non-dimmable systems with few adjustments. Moreover, the possibilities of primary energy savings from artificial lights operating in two hospitals of Europe have been identified based on measurements. The fuzzy controller has been combined with validated Radiance lighting models running an annual simulation. The Radiance model has been validated with measurements collected in the hospitals. The annual simulation indicates that energy savings of more than 35% are possible in dimmable systems, which can be increased if the controller switches the lights off when the room is un-occupied.

Acknowledgements

This work is partly funded by the EU Commission, within the research contract GREEN@Hospital (Contract Nr. 297290) a 3-year European Project co-funded by the ICT Policy Support Programme as part of the Competitiveness and Innovation framework Programme (CIP).

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