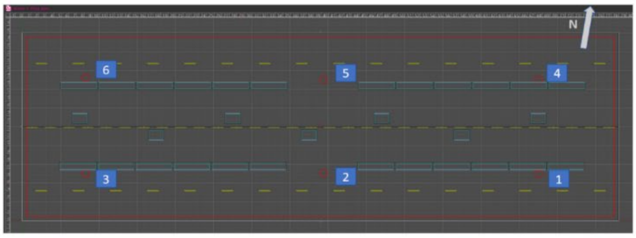
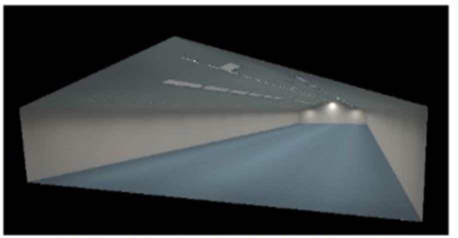
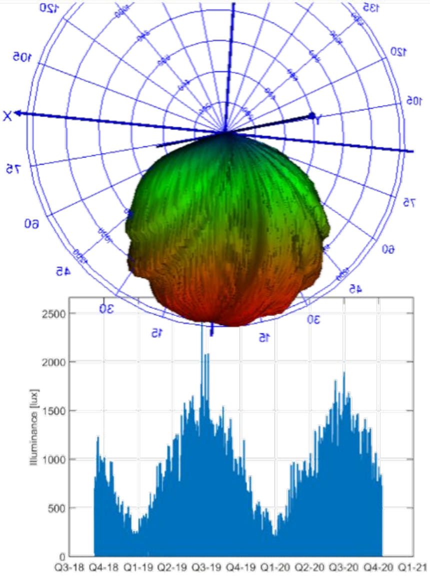
Final report

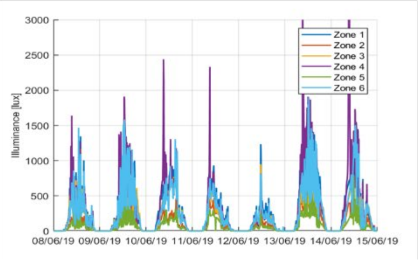
Energy saving LED smart tube

in intelligent solutions









By

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July 2021

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1. Project details

Project title	Energy saving LED smart tube in intelligent solutions
File no.	64017-05144
Name of the funding scheme	EUDP
Project managing company / institution	DTU Fotonik
CVR number (central business register)	30 06 09 46
Project partners	Allan Krogh Jensen Holding Aps and LED-TEK A/S
Submission date	12 July 2021

2. Summary

The objective of the project was to investigate the functionality and energy savings of the new LED Smart tube, an LED tube with smart sensors and metering being able to control the lighting in the immediate area through daylight and motion control. This was done through computer modelling and analysis of two years of collected data for the lighting conditions and energy consumption in a pilot installation at an industrial site. This has shown that energy savings of 40-60 % is achievable using LED Smart tubes with daylight control instead of normal LED tubes. A 26 % higher energy saving can be achieved by using distributed light control in all zones of the analysis compared to the one with lowest energy savings.

Through laboratory stress and photometric tests, it has been shown that the LED tubes intended to be used for the LED smart tube, survived the new EU endurance test with 100 % survival factor and with a lumen maintenance of 104 % at 3000 h, no visible color change and high-energy efficiency of 150 lm/W. The on/off cycling in the EU endurance test did not change the lumen maintenance compared to continuous on, showing a thermally well-constructed and robust LED tube capable of slow on/off switching, which is the basis of the LED smart tube functionality.

The LED Smart tube concept in decentralised light control will be pursued in other types of lighting products, like LED panels for offices and institutions and LED high bay luminaires for industrial illumination, for installation in old buildings were new cable installations are not economically viable. It is the hope that the project results can help promote the advantages of decentralised daylight control systems in general and ensure larger energy savings.

2.1 Dansk resumé

Formålet med projektet var at undersøge funktionaliteten og energibesparelserne i det nye LED Smart tube, et LED-rør med smarte sensorer og indbygget måling, der kan styre belysningen i nærområdet gennem dagslys og bevægelseskontrol. Dette skete gennem computermodellering og analyse af to års indsamlede data for lysforholdene og energiforbruget i et pilotanlæg i en industrihal. Dette har vist, at energibesparelser på 40-60 % kan opnås ved hjælp af LED smart tubes med dagslyskontrol i stedet for normale LED-rør. En 26 % højere energibesparelse kan opnås ved hjælp af distribueret lyskontrol i alle analyseområder sammenlignet med det område, der har den laveste energibesparelse.

Gennem laboratorie stress og fotometrisk tests er det vist, at LED-rørene, der var beregnet til at blive brugt til LED Smart tube, overlevede den nye EU-udholdenhedstest med 100 % overlevelsesfaktor og med en lumen vedligeholdelses faktor på 104 % ved 3000 h, ingen synlige farveændringer og høj energieffektivitet på 150 lm/W. On/off-cyklingen i EU's udholdenhedstest ændrede ikke lumen vedligeholdelsen sammenlignet med kontinuerlig on operation, hvilket viser et termisk godt konstrueret og robust LED-rør, der er i stand til at gennemføre mange tænd/sluk, hvilket er grundlaget for LED-smart rørets funktionalitet.

LED Smart tube konceptet med decentraliseret lysstyring vil blive fulgt op i andre typer belysningsprodukter, såsom LED-paneler til kontorer og institutioner og LED highbay armaturer til industriel belysning, til installation i gamle bygninger hvor nye kabelinstallationer ikke er økonomisk levedygtige. Det er håbet, at projektresultaterne generelt kan bidrage til at fremme fordelene ved decentrale dagslysstyringssystemer og sikre større energibesparelser.

3. Project objectives

The original idea of the project was to introduce a new type of LED SmartTube solution on the market. The company, JensenLED, had developed a new type of LED tube with metering, light and motion sensors, interactive performance and current consumption control / measurement. The concept of the LED SmartTube is based on a patent EP2044362 (B1) which due to intelligent control and sensors can result in energy savings compared to normal LED tubes between 50-90%, depending on the amount of daylight available and the degree of movement in the lit area. The patent also describes several mechanical properties that can minimize production costs and maximize energy efficiency, which we wanted to make use of with LED SmartTube. JensenLED bought the patent EP2044362 (B1), translated and registered patent in more than 20 EU countries for JensenLED SmartTube.

The original objective of the project was to complete a pilot project, technology development and production preparations, measurement and evaluation of savings potential, market style direction and various stress- and technology-test in laboratory and in an industrial environment. Further to stress and function test in identical environments as regular LED tubes to analyse the LED smart tube functionality and energy saving potential.

The project objectives had to be revised considerably as a consequence of the company JensenLED’s problems, which first led to a pausing of the project, later there was a cessation of all activities, sales of parts of the business and a practical closure of JensenLED. The objective of producing a 0-series of the LED smart tube and to install these in the pilot installation had to be abandoned.

The objectives of the revised project were therefore to make a model for the functionality of the LED smart tube and make a computer simulation and analysis of the possible energy savings. The stress and technology test in laboratory and in an industrial environment were still an important objective and was to be carried out on LED tubes without the smart functions, but otherwise identical. The laboratory test was photometric testing for energy efficiency, light distribution, color quality and long-term testing of at least 10 samples of the LED tube. The original objective of doing a lumen maintenance test over 6000 h, was changed into the new EU endurance[1] test which stresses the LED tubes through on/off switching, at time intervals that allows for maximum temperature variations.

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[1] EU regulation EU 2019/2020, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R2020&from=EN

The objective of the pilot installation was to establish a long term and high-resolution mapping of the lighting conditions in the industrial environment of a storage hall, with monitoring of the illuminance at the floor level illuminance and energy consumption of the installed LED tubes. And to use this as the basis for the computer analysis of the functionality of the LED smart tube. The new project partners, not owning the patent behind the LED smart tube, and the lighting industry generally will be able to use results of simulation and analysis of the LED SmartTube solution, to assess the potential of smart lighting concepts for further development of their own product portfolio, and overall innovation strategy.

The concept and functionality of the LED smart tube being able to control the lighting decentralised by light and motions sensors have been investigated. Stress- and technology-test in laboratory and in an industrial environment have been carried out on LED tubes, covered by the same patent as the LED smart tube, but without the smart sensors. The pilot installation should compare the functionality and energy efficiency of the LED Smart tube with normal LED tubes, through installation of these and on-site measurements. Since no production of a 0-serie was done only normal LED tubes were installed in a storage hall.

Two years of 5-minute interval data for floor level illuminance in six zones and energy consumption has given a valuable basis for analysis of the LED smart tube functionality and for daylight control systems in general. A robust calibrated optical sensor for illuminance measurement in a field of view looking at the floor below the sensor sent data to the illumicloud storage as was the intention of the LED smart tube. Computer analysis of the data has shown that energy savings of 40-60 % is achievable using LED smart tubes with daylight control instead of normal LED tubes in an industrial environment. A 26 % higher energy saving can be achieved by using distributed light control in all zones of the analysis compared to the one with lowest energy saving.

It has been shown that the LED tubes intended to be used for the LED smart tube, survived the EU endurance test with 100 % survival factor and with a lumen maintenance of 104 % at 3000 h. The on/off cycling in the EU endurance test did not change the lumen maintenance compared to continuous on, showing that the construction of the LED tubes, covered by the patent EP 2 044 362 B1, are thermally well constructed and robust. This stress test shows that the LED tubes are capable of slow on/off switching, which is the basis of the LED smart tube functionality in turning off when daylight is enough, or no motion/presence requires no lighting. The photometric testing showed no visible color change over the long-term test, and high energy efficiency of 150 lm/W.

4. Project implementation

The project started well and the first units of a functional prototype of the LED smart tube with included light sensors was made. It was tested and analysed by DTU Fotonik for the response and linearity of the lux sensor, and the photometric and energy efficiency properties of the LED tube itself. Work on optical design of the light intensity distribution and acceptance angle of the light sensor for the LED tubes at high installation heights were initiated. The pilot project was started with installation of LED tubes in a storage hall in Kjellerup. A power monitoring system was installed and custom designed optical sensors for monitoring the illuminance at the floor level was developed and installed. A cloud based system[2] for storing the data from the pilot installation was created and storage of illuminace data was initiated and has run for the majority of the project period.

The company JensenLED tried several times getting the LED smart tubes produced in a 0-series but did not succeed with this. The project was paused due to this, and later there was a cessation of all activities, sales of parts of the business and a practical closure of JensenLED. Therefore, JensenLED had no employees and

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[2] https://illumicloud.com/

could no longer run or participate as partner in the EUDP project. This was at a time were DTU Fotonik had invested a lot of time and effort into the project, and it was decided to try to reconstruct and finish the project.

DTU Fotonik contacted LED-TEK A/S and Allan Krogh Jensen and asked them to participate in a reconstructed project. LED-TEK had acquired employees from the closed company and Allan had been employed there and was behind the idea of the LED smart tube. A revised project description and budget was approved by EUDP. The patent was owned by Jensen IP, not part in the revised project. Hereafter the pilot installation was examined, data collected for almost two years of operation, and the optical sensors were taken down from the installation. A model and simulation of the functionality of LED smart tubes based on the two years of data from the pilot installation was carried out. Photometric and long-term testing of LED tubes produced under the patent EP2044362 (B1) and sold by LED-TEK A/S was carried out over 6 months. Results of the project have been accepted for publication at CIE 2021 conference, and will be part of an article in the industry journal LYS of Danish Center for Lighting in autumn 2021 after the project has been completed.

So the project implementation did not develop as foreseen and the original milestones agreed upon were not fulfilled. The problems with production of 0-series was a small risk in the project, and other circumstances must have led to the closure of the company JensenLED. This was an unforeseen risk with conducting the project, and resulted in problems that was not expected. The reconstructed project has been carried out according to the reconstructed plan and it's milestones has been achieved.

5. Project results

The original objective of the project in developing and producing 0-series of the LED smart tubes to be tested in the pilot installation and for market introduction was not obtained. This objective had to be revised due to the company JensenLED's business problems with getting the LED smart tube produced, further cessation of activities, which has led to sales of parts of the business and closure of JensenLED. Due to this a reconstruction and continuation of the project with new partners was established and the objectives of the project were revised. The production and market introduction of LED smart tubes were taken out, and instead to conduct a test, simulation and analysis of the LED Smart Tube usage and functionality compared to conventional LED tubes. This was to be based on two years data for illuminance and power consumption in the industrial environment, Further, to perform photometric testing of the equivalent LED tubes without the smart functions, including an endurance test of the LED tubes, required by the new EU regulation which comes into force in September 2021. These new objectives has been obtained and the technological and commercial results are described in the following sections.

5.1 Technological results

5.1.1 LED smart tube

A functional prototype of the LED smart tube with light sensors was made. It was tested at DTU Fotonik for response of the light sensors. A measurement setup was constructed where a reference photometer[3] was placed right next to the LED tube's light sensor in the same plane. This is shown on the photos in Figure 1.

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[3] Radiolux 111, PRC Krochmann, Ser. No. 130917 Calibrated 3.8.2016.

Figure 1. Photos of the LED tube characterization setup; left: reference photometer mounted next to LED tube sensor, middle: point light source illuminates the LED tube setup, right: LED tube setup illuminated a neutral grey painted wall.

The LED tube setup is placed on a camera stand with wheels, making it easy to change the position. Two types of measurements were made, the response and linearity of the lux sensor, and the photometric properties of the tube itself. The response and linearity (and as such the calibration) of the measurements done of the lux sensor in the tube have been done using a Ø60mm LED light source which was illuminating the LED tube setup at a varying distance, see middle photo in Figure 1. The result of this measurement is shown in Figure 2 on the left where the measured estimated illuminance for two different resistors in the photodiode setup as a function of the measured reference illuminance when the LED light source illuminated the lux sensor directly, and on the right when the LED light source illuminated the wall.

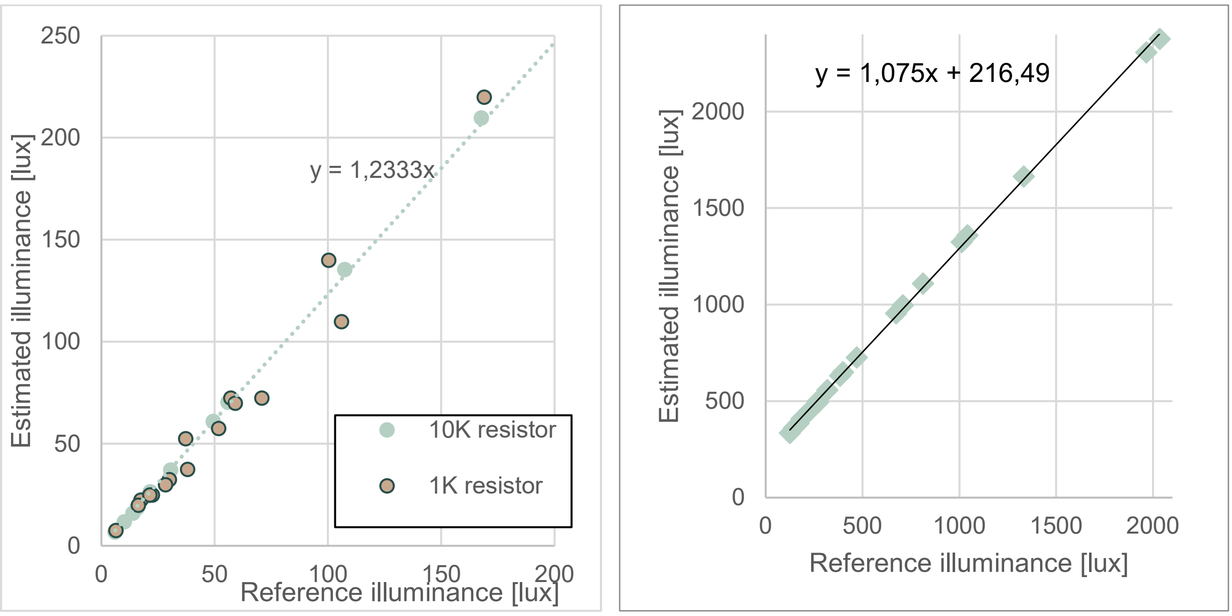

Figure 2. Measurement results of LED tube setup, left: measured estimated illuminance as a function of the measured reference illuminance for two resistor values, right: measured estimated illuminance as a function of the measured reference illuminance when the LED tube illuminates the wall.

It is observed that for the low illuminances 0-200 lux there is a better linearity using the 10 K resistor. The graph to the right in Figure 2 shows the estimated illuminance in the setup illuminating the wall. A good correlation is observed with an offset of 216 lux. The conclusions are that the resistor must be optimized for a good response in the illuminance range that the LED tube will see under operation and that the angular response needs to be designed for the application. This is done for the sensors in the pilot installation.

Photometric characterization of three LED tubes was performed at DTU Fotonik, to obtain values of luminous flux, energy efficiency and light intensity distribution for simulations. The measurement results from integrating sphere and goniophotometer measurements is shown in Table 1.

Table 1. Results of photometric testing of three LED tubes, left: integrating sphere measurement results, right: goniophotometer results.

Tube Identifier #	L31386	L31387	L31388
Measurement ID #	M31851	M31852	M31853
Power [W]	24,4	23,9	23,75
Luminous Flux [lm]	3627	3528	3529
Luminous Efficiency [lm/W]	148,9	147,5	148,6
Color Rendering index Ra [-]	82,76	82,8	82,7
R9 [-]	4,4	4,8	3,96
Correlated Color Temp [K]	4110	4129	4115
DUV [-]	8,1E-04	6,2E-03	6,7E-04
x [-]	0,376	0,375	0,376
y [-]	0,376	0,375	0,375

Tube Identifier #	L31386	L31387	L31388
Measurement ID #	M31854	M31855	M31856
Power [W]	24,4	23,9	23,8
Luminous Flux [lm]	3648	3574	3573
Luminous Efficiency [lm/W]	149,3	149,2	150

The LED tubes has a measured efficiency of 149 lm/W and the two types of measurements are consistent within 1.2 %. The absolute expanded measurement uncertainty is approximately ± 4.5 % for a confidence level of 95 %. In Figure 3 the measured spectral power distribution is shown to the left and the light intensity distribution (LID) to the right. This has been exported to an Eulumdat file and used in the simulation model, see Figure 6.

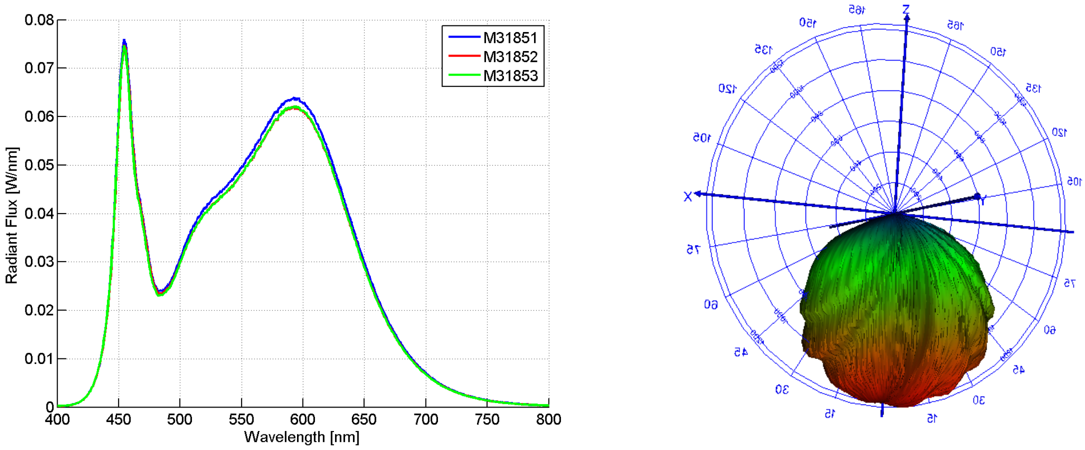

Figure 3. Left: measured spectral power distribution as a function of wavelength for the three LED tubes, right: 3D false color image of light intensity distribution for LED tube.

The LED tubes have a very good color rendering for the application, with a more than adequate color rendering index (CRI) of 83 (According to DS/EN 12464-1[4] the minimum is 60 see Table 2) and a specific CRI for red objects (R9) of 4.

5.1.2 Pilot installation

A storage facility/hall at Steens group (hal 16) in Kjellerup in Jutland was chosen for the pilot installation and test. The hall is 25x78 meters with an area of 1950 m^2. It is shown in Google maps images on Figure 4 and photo from inside the hall in Figure 5. It is used for storage of cardboard boxes on pallets, which in some situations with high stacks blocks the light from the luminaires.

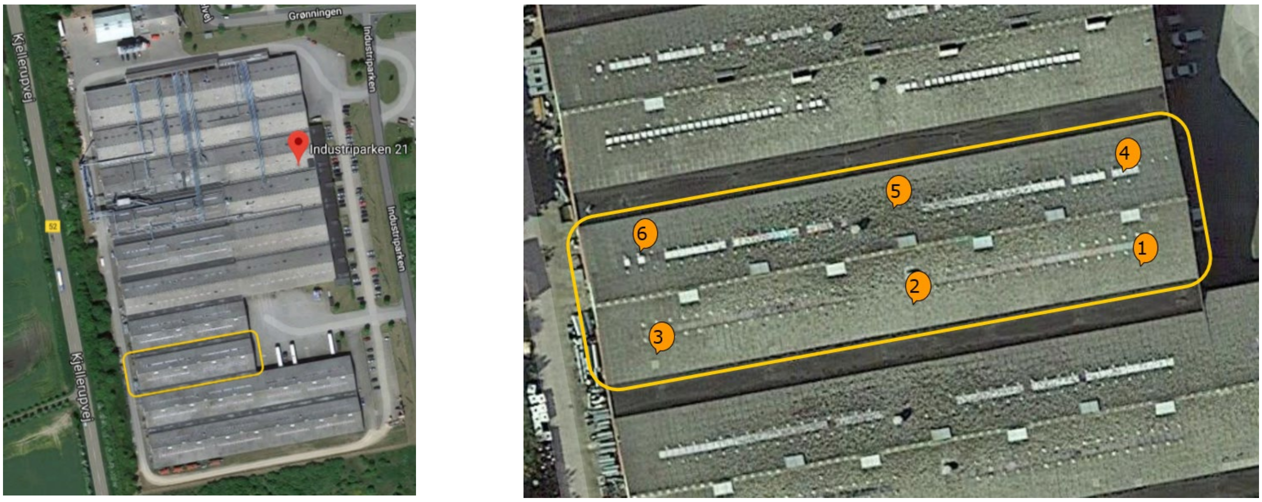

Figure 4. Images from google maps showing the Steens group in Kjellerup, on the image to the right a zoom of the hall is shown with indication of the LuxSensor placements. North is up op the images.

Figure 5. Photos from the hall, with storage of cardboard boxes on pallets.

A 3D model of the hall has been built in Relux® with LED tube luminaires and skylights, so that lighting calculations can be done for the artificial light and for daylight. The model and examples of artificial light calculations are shown in Figure 6. The large amount of carboard boxes in the hall makes it difficult to establish a model that can predict the actual illuminance levels. Therefore, a pilot installation has been made with optical sensors monitoring the illuminance on the floor at six positions in the hall.

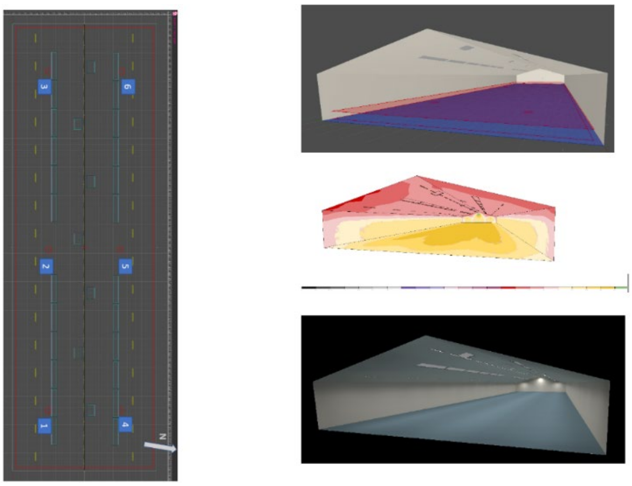

Figure 6. Images from the Relux® simulation model of the lighting in the hall. Left: overview from the top with skylight windows (blue rectagles) LuxSensor positions (red circles), luminaires with LED tubes (yellow lines). Right top: 3D with easurement planes, right middle: false color illuminance distribution for artificial light, right bottom: luminance image for artificial light.

According to the standard DS/EN12464-1[4] the illuminance at the task level has to be at least 100 lux as seen in Table 2. Here we relate the task level to the floor level, and maintaining 100 lux at the floor level will also ensure >100 lux at higher task reference planes.

Table 2. Table 5.4 from DS/EN 12464-1[4] p. 24

Table 5.4 — General areas inside buildings – Store rooms, cold stores

Ref. no.	Type of area, task or activity	$\bar{E}_m$ lx	UGR_L –	U_o –	R_a –	Specific requirements
5.4.1	Store and stockrooms	100	25	0,40	60	200 lx if continuously occupied.
5.4.2	Dispatch packing handling areas	300	25	0,60	60	

5.1.3 Sensors

For the pilot installation it was required to be able to measure and monitor the illuminance at the floor level and the power consumed. For this purpose custom designed light sensors was installed in the hall together with power logging devices installed on two groups covering the 16 luminaires along the two side wall of the hall. Each luminaire has two 30 W LED tubes installed. Each group has a power consumption of approx. 960 W when alle luminaires are lit. Power measurement have been done and logged every 5 minutes.

It is very difficult or practically impossible to install direct illuminance sensors at the floor level since people and trucks travel along the narrow pathways of the hall. A custom designed light sensor was developed for this measurement purpose. It was designed to hang 4-5 m above the floor where it is out the way for the machines and people working. It collects light reflected and scattered of a circular area on the floor with a diameter of approximately 1.5 m at 5 m distance. This limited angular acceptance is achieved by placing a lens in front of the light sensor. The sensors are based on a Raspberry Pi microcomputer and an RGB sensor. The sensors are in WiFi connection to the router installed in the hall and can via this be controlled and send

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[4] DS/EN 12464-1:2011, "Light and lighting – Lighting of work places – Part 1: Indoor work places", new version DSF/EN 12464-1:2021 to replace this is in production.

data through an internet connection. The sensor is programmed to restart every 60 s and perform one measurement and save the data internally and send the data to the cloud service develop in the project: illumicloud.com. From here data could be monitored and visualized.

Figure 7. Photos from installation hall, left: five of the LuxSensors with long wires to be hung from the ceiling, right: routers for communication and installation of power measurement.

The sensors have been calibrated by placing a reference photometer[3] on the floor directly under the sensor, at the marked spot. This situation is illustrated in Figure 8. At this point illuminance measurements have been taken over at least 5 minutes corresponding to 5 measurement point by the sensor to be calibrated. A daytime illuminance situation with both daylight from the roof windows and artificial light from the LED tube luminaires is used for the calibration. Illuminances were around 1000 lux, and it is assumed that the calibration can be used for 10-20000 lux.

Figure 8. Photo of on-site calibration where the field of view of the luxsensor is indicated by the green dashed cone, the reference photometer is connected to the computer and measured over time.

After this has been done for all 6 sensors, a correlation analysis between the reference illuminance measurements and the corresponding sensor measurements. An example of this is shown in Figure 9. The ratio between the reference illuminance and the sensor signal is the calibration factor, and Φ_V , which is the illuminance on the floor measured in lux can be expressed as

$$\Phi_V = \frac{\Phi_V^{kal}}{S_V^{kal}} \cdot S_V$$

where S_V is the signal form the LuxSensor.

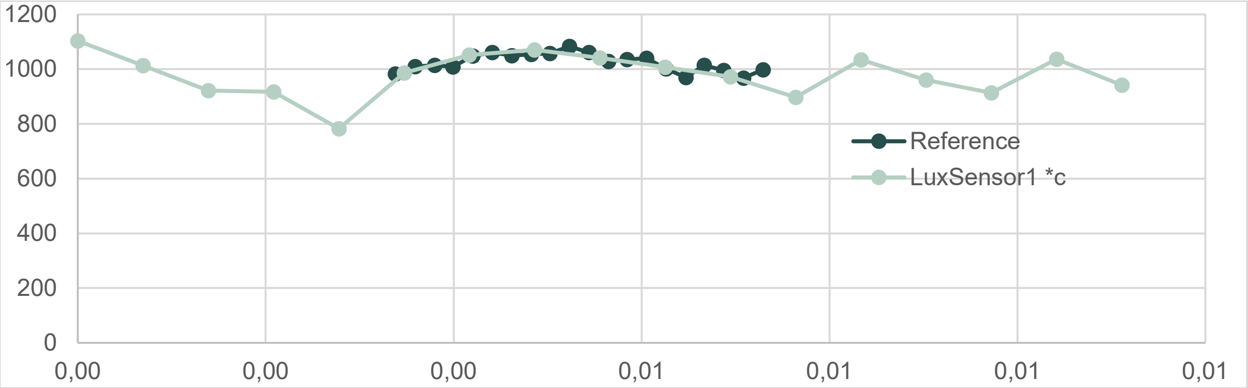

Figure 9. Graph showing the measured reference illuminance at the floor as a function of time and the LuxSensor1 readings multiplied by the calibration factor of 1.57 to get correspondence between these.

For the example for LuxSensor1 in Figure 9 the calibration factor has been determined to be 1.57 ±0.03 which corresponds to 2 %, which is regarded as a very good correlation. All 6 sensors have approximately the same value for the calibration factor as shown in Table 3, where it can be seen that LuxSensor 1 has the lowest value and LuxSensor 6 the highest value.

Table 3. List of LuxSensors, the identification E#, name, place of installation, and determined calibration factor.

No.	DTU E#	Name	Installation Area	Calibration factor
1	E30051	LuxSensor1	Non-smart Area East	1,57
2	E30052	LuxSensor2	Non-smart Area Center	1,80
3	E30053	LuxSensor3	Non-smart Area West	1,75
4	E30054	LuxSensor4	Smart Area East	1,71
5	E30055	LuxSensor5	Smart Area Center	1,75
6	E30056	LuxSensor6	Smart Area West	2,08

The calibration factors for the individual LuxSensors have been implemented in the software program running on each Raspberry Pi computer and the values stored and sent to illumicloud.com. The pilot installation has run stable for almost two years and the data is used in 5.1.4 Simulation of energy savings.

5.1.4 Simulation of energy savings

A simulation model for the LED Smart Tube was made since it was not possible to put the LED Smart Tube into production. The simulations model is based on the large amount of data gathered at the pilot installation during almost 2 years, reg. power consumption of existing tubes, and actual lux levels on the floor. The purpose of the model was to estimate the power that could have been saved at the pilot-installation if the ordinary LED tubes were replaced with Smart LED tubes. The model is implemented in Excel. It performs an instant calculation of the power saved in each 5 min. Interval during the whole period where lux and power data are available. Since the lux is not measured at each LED tube as originally planned, but instead by 6 stand-alone lux sensors. We have a simulation run for each of those sensor zones, zone 1 to zone 6 in Figure 10. The consumed power is only measured for each row of LED tube fixtures on the north and south side, covering three zones. The power measurement used is divided by 3 to approximate the power consumption of one zone, The measured power as a function of time is shown in Figure 11.

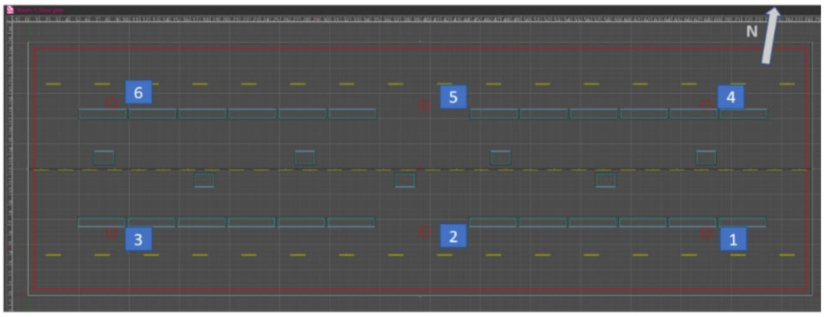

Figure 10. Overview of the hall with marking of skylight windows (blue rectangles) LuxSensor positions (red circles) and numbers according to Table 3. Luminaires with LED tubes (yellow lines).

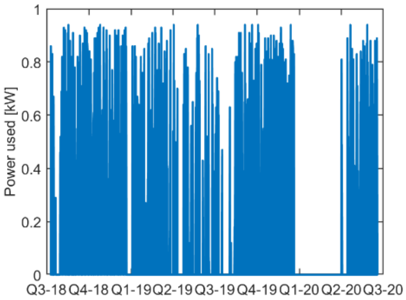

Figure 11. Measured power consumption as a function of time over 2 years for the three zones 1,2 and 3 combined.

The LED Smart tubes in the simulation model is adjusted to a setpoint of 100 lux on the floor, according to Table 2. The simulation is done in intervals of 5 minutes. The LuxSensors has a time resolution of 1 minute and has for the calculation model been interpolated to the power measurements timestamps of 5 min intervals.

In Figure 12 the measured illuminance in the six zones at the floor level is shown as a function of time over 2 years, the graphs are shown according to their positions shown in Figure 10.

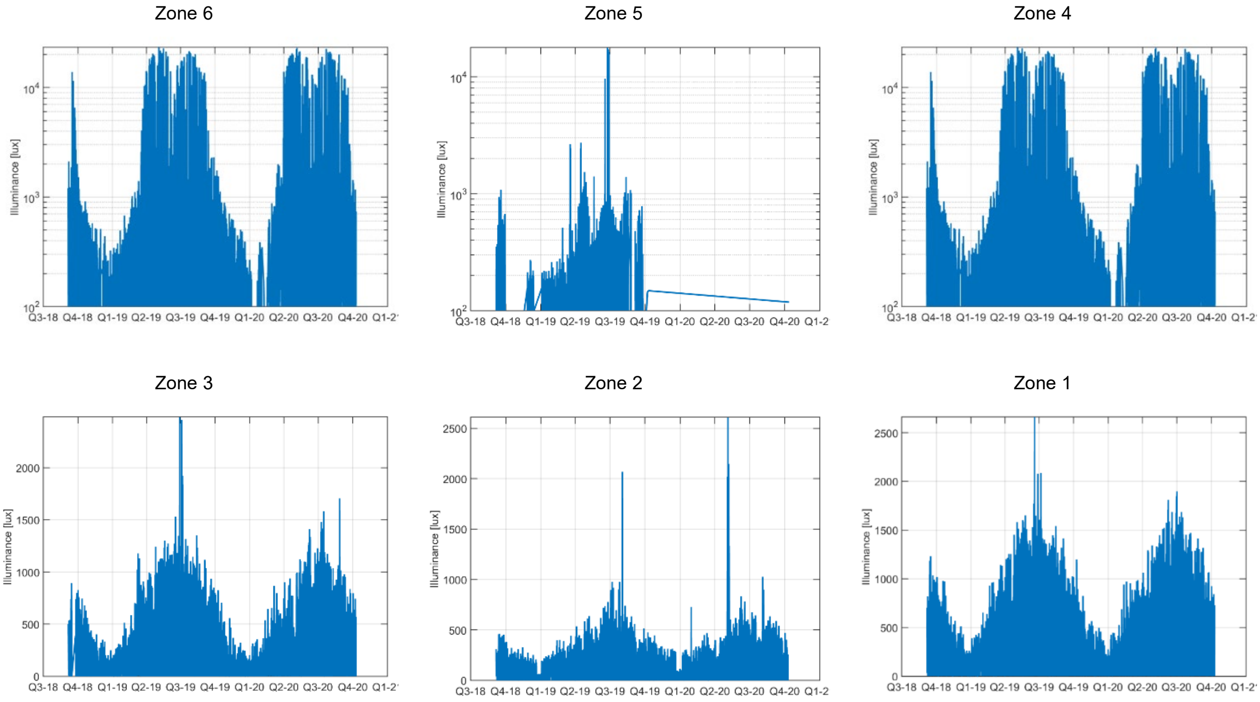

Figure 12 Measured illuminance in the six zones at the floor level as a function of time over 2 years. Note that the zones 4,5 and 6 located on the north side of the hall has much more incident daylight and the graphs for these use logarithmic scales for the illuminance.

The graph for zone 1 shows the yearly changes in illuminance levels, with lowest values at Q1 in 2019 and 2020, and the highest values in summertime, Q3. The levels reproduce but with some variations for the two years. The zones 4, 5 and 6 are at the north side of the hall and daylight / direct sunlight can reach these zones through the skylights as shown in Figure 10, this is not the case for zones 1, 2 and 3 on the south side, and hence the measured illuminance level are approximately 10 times higher, and these graphs use logarithmic scales. The sensor in zone 5 is seen to have been malfunctioning in the last year. Zones 2 and 5 are in the middle of the hall, there is only one skylight window over these zones, and hence the illuminance here is much lower than at the other zones where more skylights are placed. In Figure 13 the measured illuminance in the six zones is shown for two representative weeks in summer and autumn 2019. It shows the large daily variations and that zone 4 and 6 have the highest values.

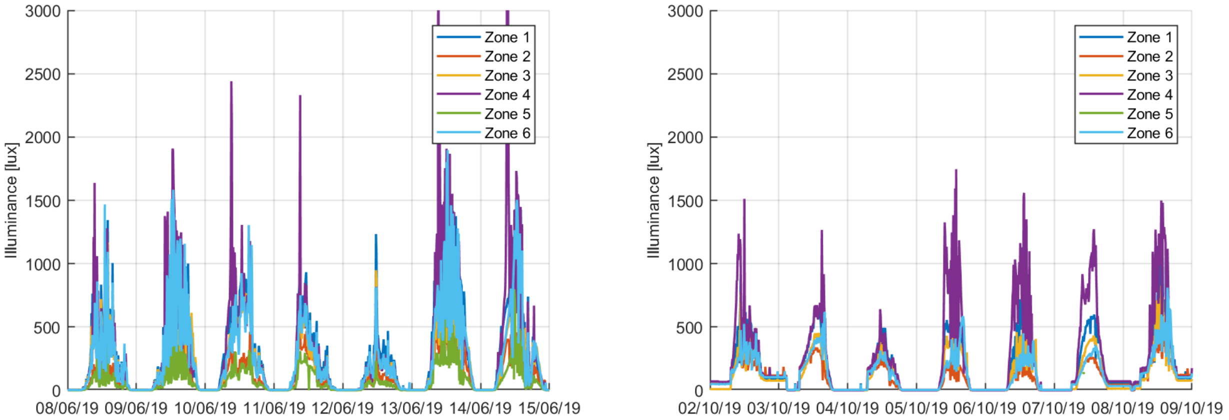

Figure 13 Measured illuminance in the six zones at the floor level as a function of time over left: a summer week in June 2019, right: an autumn week in October 2019.

Offset light levels originating from the LED tubes alone were calculated by averaging the light measured, when there was no daylight input, but the LED tubes were turned on (January and February before 7 AM). These offset illuminances are shown in Table 4 for the six zones, where it is seen that zone 3 and 6 are not well lit. The energy price used in the model was set to 2.25 DKK[5]. The model calculates the power consumption of a Smart Tube installation for every 5 min. interval. As inputs it takes the measured illuminance or lux level, and the measured power consumption of the ordinary LED tubes. Based on the power consumption it can detect if light was turned on or not. The amount of daylight is calculated by subtracting the lux provided by the LED tubes (if they were turned on) from the measured lux level. The offset lux level from the ordinary LED tubes is assumed to be a constant for each zone, as described above.

The required illuminance level is 100 lux, see Table 2. So, the surplus of light can be calculated by subtracting the required amount of lux from the daylight lux level. This surplus of light can be converted into a power over consumption. This is done by a simplified linear interpolation. Power consumption of the ordinary LED tube and a scenario where Smart Tubes were installed instead are calculated, and comparisons of the two scenarios regarding energy consumption and energy savings can be made. The results of this analysis for each zone over the two years of data are shown in Table 4.

Table 4 Average illuminance on floor from LED tubes and results of analysis on energy consumption, the energy savings and relative energy savings in each individual zone if LED Smart Tubes were installed instead of ordinary LED tubes.

Zone	Av. Illuminance LED tubes only [lux]	Energy consumption per year, ordinary LED tubes [KWh]	Energy savings per year, Smart Tubes [KWh]	Rel. savings per year [%]
1	92	844,85	486,8	57,6
2	107	844,85	455,0	53,9
3	63	844,85	354,7	42,0
4	105	844,85	508,4	60,2
5	97	844,85	(270,0)	(32,0)
6	71	844,85	437,3	51,8
Average				53,1

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[5] source: nettopower.dk

The illuminance on the floor when only LED tubes are on and no daylight is shown for the zones, and it can be seen that all are around 100 lux, except zone 3 and 6 which only has 63 and 71 lux. The analysis of zone 5 might be affected by the lack of data, see Figure 12, and the data has been taken out of the comparison. Looking at the energy savings over the 6 different zones it is clear to that there is a big variation from 42% in zone 3 to 60% in zone 4. The average relative energy savings if LED Smart Tubes were installed instead of ordinary LED tubes is 53%. The variations depend on the daylight incident in the various zones, which again depends on the skylight positions and orientation as described above. But it also depends on shadows caused by the cardboard boxes that are piled up and located at different positions in the stock, and that those boxes are often moved around causing new kind of shadows. The LED tube illuminance level is lower in zone 3 and 6, which affects the energy savings in these zones since the LED Smart tubes has to be on for longer times. Before starting this project, we also made an calculation for estimating the power savings that could be provided by an LED Smart Tube. Here the savings due to daylight control was estimated to be 30% energy savings. This assumption was based on a scenario where the required lux is 200 (like offices and classrooms etc.), so the power saving is obviously higher if the required lux is only 100 as in our test installation and simulation model. So, an average energy saving of 53% as the simulation model says is in sync with our first assumptions.

This big variance in the local daylight contribution has a huge effect on the power saved. If for instance we let a central lux sensor control the light for the entire room and that sensor was placed in zone 3 (with only 42% power saving), then the total power saving of the hall would have been much worse. See Table 5. Table showing the energy saving if a central daylight controller placed in zone 3 (worse case) were used, vs. decentral daylight control.below where the decentral lux control is compared with a traditional central lux control, where the lux sensor is placed in zone 3.

Table 5. Table showing the energy saving if a central daylight controller placed in zone 3 (worse case) were used, vs. decentral daylight control.

Zone	Energy consumption per year, ordinary LED tubes [KWh]	Energy savings per year, decentralised lux control [KWh]	Energy saving per year, central lux sensor in zone 5 [KWh]
1	844,85	486,8	354,7
2	844,85	455,0	354,7
3	844,85	354,7	354,7
4	844,85	508,4	354,7
5	844,85	-	-
6	844,85	437,3	354,7
Total		2242,1	1773,3

It can be seen that the decentral lux control that is used in the LED Smart Tube, provides a total energy saving for alle zones of 2242 KWh. Where the central lux control, that adjusts the lux level in all 6 zones according to the lux level measured in zone 3, only provides a total energy saving of 1773 KWh. This equals to a 26 % higher energy saving when using decentralised lux control compared to centralised lux control.

5.1.5 Long term test

The lifetime of the LED tubes are of high importance for the energy saving calculations and return of investment for an installation. For many years the lifetime of LEDs and LED lamps and luminaires have been characterised by the luminous flux maintenance, e.g. L70. In 2019 the EU published a new regulation EU 2019/2020[1] for ecodesign requirements of light sources and separate control gears, which will come into force by 1 September 2021. With this a new endurance test to verify their lumen maintenance and survival factor was described. It is a switching cycle test, where the light source is operated for 1 200 cycles of repeated, continuous switching cycles without interruption. One complete switching cycle consists of 150 minutes of the light source switched ON at full power followed by 30 minutes of the light source switched OFF. The hours of operation recorded (i.e. 3 000 hours) include only the periods of the switching cycle when the light source was switched ON, i.e. the total test time is 3 600 hours. This is a valuable test for the LED smart tube that needs to tunn on and off regularly depending on the daylight and motion in the lit area.

An LED tube (LED-JL1112 T8 highpower flickerfree[6]) from LED-TEK, under the patent EP 2 044 362 B1 was chosen for the long term testing. It has a power usage of 25 W, a correlated color temperature of 4000K, a nominal luminous flux of 3750 lm and a length of 150 cm. The EU endurance test was performed on 11 samples of the LED tubes. Along with the EU endurance test, 5 samples of the LED tube were subjected to a continuous ON test. Prior to the testing all the 16 samples were measured using a 2m integrating sphere spectroradiometer setup. A room where the ambient temperature could be controlled to approximately 21°C and that can be kept dark was established. A metal rack with 15 fixtures for 150 cm LED tubes was prepared, as shown in Figure 14. The LED tubes are installed with the main direction of illumination downwards according to normal operation. An UPS is used for power supply and a programmable outlet controlled the ON/OFF switching of the 11 samples. A temperature sensor monitored the ambient temperature and one the tube temperature of one LED tube.

After the 1200 cycles, i.e. after approx. 5 months, the survival factor was determined by counting the number of operational samples after the test. At least 9 out of 10 light sources of the test sample must be operational after completing the test. For the not failed samples the final luminous flux measurements are made in the 2m integrating sphere spectroradiometer. The average lumen maintenance factor X_{LMF} % is determined by averaging the lumen maintenance factor for each of the samples that did not fail. This needs to be compared to the producers stated lifetime for L70B50. For this LED tube the datasheet states: >50000h @L80B10, which corresponds to at least 26000 hours for L70B50, and for this the average lumen maintenance factor has to be compared with a minimum value of 96%[1].

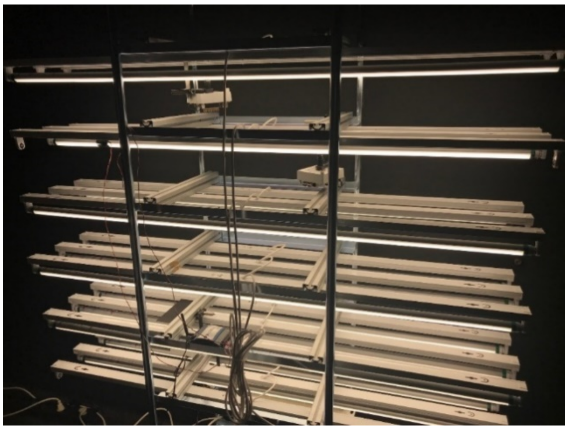

Figure 14. Photo of the long term test setup for LED tubes.

The results on initial and 3000 h luminous flux are given in Table 6, which includes a calculation of the degradation/maintenance of the luminous flux compared to the initial flux.

It is seen that all samples of the LED tube survived the endurance test, hence the survival factor is 100 %. The new EU directive allows for one of 10 samples to fail, but this did not occur. The average luminous flux maintenance is 103.7 %, which is clearly larger than the 96%, which is the minimum allowed. The fact that there is an increase in luminous flux is not an unusual behavior for LED products.

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[6] https://www.led-tek.dk/produkter/led-produkter/led-jl1112-t8-highpower-flickerfree-lysroer-25w-4000k?ref=12132,
datasheet: https://www.led-tek.dk/media/389478/datablad-led-jl-t8-highpower-flickerfree-serie.pdf

Table 6. Results of the EU endurance test for 11 samples of the LED tube

ID#	Luminous flux Initial flux [lm]	 3000 h flux [lm]	 Faliure Yes/no	Degradation [%]	Maintenance [%]
L31855	3669	3810	no	-3,8	103,8
L31856	3730	3878	no	-4,0	104,0
L31857	3761	3890	no	-3,4	103,4
L31858	3794	3938	no	-3,8	103,8
L31859	3779	3910	no	-3,5	103,5
L31860	3746	3874	no	-3,4	103,4
L31861	3764	3896	no	-3,5	103,5
L31862	3811	3947	no	-3,6	103,6
L31863	3644	3776	no	-3,6	103,6
L31864	3756	3891	no	-3,6	103,6
L31865	3703	3850	no	-4,0	104,0

The measured power for the tubes is constant, within 0.4%, throughout the measurements, hence the luminous efficiency also increases as the luminous flux. Along with the EU endurance test 5 more samples were run continuously and measured every 1000 h according to IES LM-84[7]. In Figure 15 the relative luminous flux is shown as a function of operation time, for these 5 samples together with the 3000 h measurements for the 11 samples of the EU endurance test.

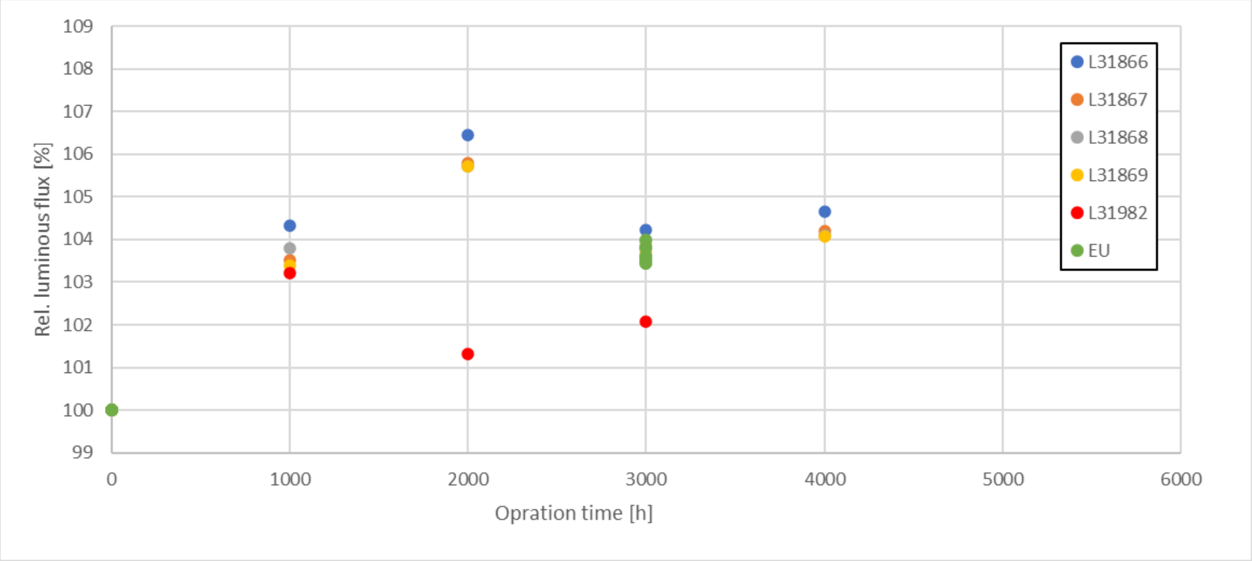

Figure 15. Measured luminous flux relative to the initial flux at 0 h for 11 LED tubes at 3000 h (EU) and for 5 LED tubes at 1000, 2000, 3000 and 4000 h.

It is observed from Figure 15 that the relative luminous flux increases until 2000 h where a maximum of approximately 106 % is achieved, except for one sample that falls to 101%. At 3000 h there is a good agreement

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[7] IES LM-84-20 “Approved Method: Measuring Optical Radiation Maintenance of LED Lamps, Light Engines, and Luminaires”, https://www.techstreet.com/standards/ies-lm-84-20?product_id=2206849

between the 11 samples in the on/off cycle test and the 4 samples that was continuously on. Another parametric failure can occur if the color of the light changes too much, beyond a six step MacAdam ellipse[Error! Bookmark not defined.]. In Figure 16 is shown the measured chromaticity in the 1976 CIE (u’,v’) diagram.

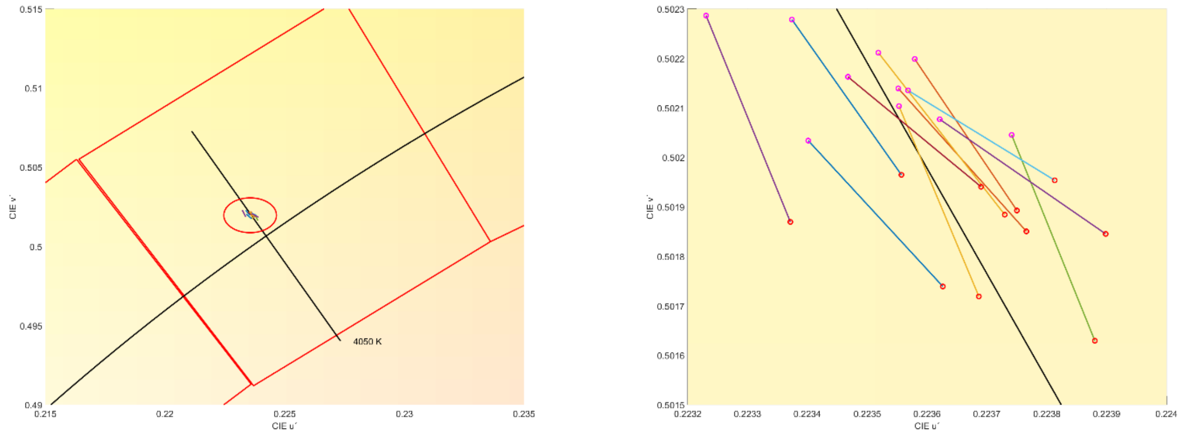

Figure 16. CIE1976 diagram showing the chromaticity coordinates of the light from the 11 LED tubes with a red circle showing the 1 step (u’,v’)-circle, right: a zoom of this diagram showing with red circles the initial coordinates and purple circles showing the end coordinates after 3000 h test.

On the graph to the left, all the measured chromaticities is observed to be within a 1-step (u’,v’) circle, corresponding to a 1-step MacAdam ellipse, which means that it would be difficult to see a variation in the color of the light from the different samples. On the graph to the right a zoom to within the 1-step circle is shown. Here the chromaticities measured initially (red circles) and after 3000 h (purple circles) can be identified. There is a small change in almost the same direction and magnitude for all samples. The average correlated color temperature has been determined to be 4048 K and 4050 K after 3000 h operation. This shows a very stable color over the 3000 h, and the change in 2 K is measurable through the repeatability, but very small compared to the absolute uncertainty, of the integrating sphere spectroradiometer. The long term testing and on/off cycling of the LED tubes did not show a degradation that could be used for better simulation of the lifetime of the LED tube installation, than from lumen maintenance.

5.2 Commercial results

The obtained commercial results are not as many as intended in the original project, since there has not been a production of a 0-series of the LED smart tube and no market introduction have been made. An important commercial result of the energy savings simulation for LED smart tube in the pilot installation, is the prediction of the return of investment (ROI) when installing LED smart tubes instead of ordinary LED tubes with same high energy efficiency. A simplified ROI is calculated by dividing the total installation cost (upfront costs) with the yearly economic savings due to lower power consumption. The results of calculation this are shown in Table 7. The total installation cost of a smart Tube is estimated to be 300 DKK at high volume installations. In this simulation one zone is covered by 10,66 LED tubes (1/3 of a row of tubes). A higher installation cost will increase the ROI and vice versa.

The results shows that a simplified ROI varies for the individual zones and is between 2,8 and 4,0 years. Results for zone 5 is not considered as explained in the previous section. So very dependent of the actual scenario reg. daylight contribution. The ROI may be shorter when taking other controls like motion sensors for occupancy into account. These results will be used by LED-TEK, for other types of LED luminaires, like LED highbay luminaires with integrated light sensor.

Table 7. Results of analysis on energy consumption, the energy savings and relative energy savings and simplified ROI in each individual zone if LED Smart Tubes were installed instead of ordinary LED tubes.

Zone	Power consumption per year, ordinary LED tubes [KWh]	Power savings per year, Smart Tubes per year [KWh]	Savings per year [%]	Simplified Return on Investment (ROI) [years]
1	844,85	486,8	57,6	2,9
2	844,85	455,0	53,9	3,1
3	844,85	354,7	42,0	4,0
4	844,85	508,4	60,2	2,8
5	844,85	(270,0)	(32,0)	(5,3)
6	844,85	437,3	51,8	3,3
Average			53,1	3,6

The new EU regulation**Error! Bookmark not defined.** requires that suppliers of LED lighting products register and enter p roduct performance data for the lighting product into the EPREL product database[8] by September 1, 2021. The new EU endurance test has not been used very much yet, and knowledge for LED-TEK on how their LED tubes perform under this test is vital for the documentation. Compliance testing will check the survival factor and the lumen maintenance with the declared L70B50 lifetime. The LED tubes tested here had no trouble in passing the test, and LED-TEK can use this information in registering their LED products in EPREL.

For DTU Fotonik there is a possibility to provide the EU endurance test as a commercial service, in the testing and characterization of lamps and luminaries using the procedures established. This may be important for many LED lighting product manufacturers.

5.3 Dissemination

A DTU orbit permanent homepage has been established for the project with references to publications and activities related to the project. The homepage can be accessed via:

https://orbit.dtu.dk/en/projects/energy-saving-led-smart-tubes-in-intelligent-solutions

The project ideas/results have been disseminated at talks/events/publications:

- Corell, D. D., Dam-Hansen, C., Thorseth, A. “Comparison of luminous flux maintenance methods, continuous vs. on-off cycles”, CIE 2021 Midterm conference “Light for Life - Living with Light” Malaysia, Sept 2021 https://malaysia2021.cie.co.at/.
- Dam-Hansen, C., Thorseth, A. og Corell, D. D., “Levetid for LED belysningsprodukter”, working title to be published in LYS 3-2021.
- Dam-Hansen, C., Corell, D. D., & Thorseth, A. (2020). DoLEDLast? LYS 2-2020, p. 25.
- Dam-Hansen, C., Kenneth Munch, “Status for LED og nye lyskilder“. Invited talk at Lysets Dag 2020 “Lys og de 17 verdensmål”, 22 Oct 2020, https://backend.orbit.dtu.dk/ws/portalfiles/portal/238422635/Pr_sentation_Lysetsdag_2020.pdf
- Solid State Lighting Annex Expert Seminar, Organized by Carsten Dam-Hansen, Anders Thorseth, Dennis Dan Corell & Linda Christel, DTU Fotonik, Risø, 7 Oct 2019
- International Seminar on Certification, Standards and Requirements of Solid State Lighting, SSL Annex seminar Seoul Korea, 4 Apr 2019.

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[8] https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/product-database_en

- “Seminar on photometric measurements and color performance of solid state lighting”, with visiting NIST fellow Yoshi Ohno, organized by Anders Thorseth and Carsten Dam-Hansen, DTU Fotonik, Risø, 16 Aug 2018.

The work in IES on LED lifetime has resulted in:

- Hulett, J., Belyaev, A., Bloomfield, C., Bretschneider, E., Feldman, A., Fletcher, K. C., Harada, Y., Jianzhong, J., Kotrebai, M., Liepmann, K., Lockner, J., Miller, C., Ohno, Y., Radkov, E., Thorseth, A., Tuttle, R. & Zong, Y., “IES LM-80-20 Approved Method: Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays, and Modules”, 2020, Illuminating Engineering Society. 23 p.

6. Utilisation of project results

6.1 Utilisation of technological results

The technological results from the analysis of LED smart tube usage and functionality based on the simulation of two years of data in the pilot installation will be utilised by all project participants. The project have paved the way into further investigations of the benefits regarding decentralised or distributed daylight control. Having more daylight sensors in a room increases the cost of an installation, but the advantages is also significant regarding energy savings. It’s the hope that the results of this project can help promote the advantages of decentralised daylight control systems in general. The idea about the LED Smart Tube is not dead but of course there needs to be a balance between having a daylight sensor at all light sources, and the overall cost of the installation. The team behind this project has the intentions of future projects within this field.

It will probably not be in the form of LED smart tubes that the technology will be used, but the smart sensor functionalities will be used in other types of LED products. This is because the market for and sales of LED tubes for replacement of fluorescent tubes in old T5/T8 fixtures are decreasing, which is due to the relatively low cost of new LED panels/luminaires that can replace these fixtures. These new LED panels/luminaires however, is often supplied with a built in motion sensor in each lamp, when the existing old wiring is not prepared for an installation with central daylight and motion sensor, which requires 2 extra wires for the DALI control signal.

Examples of buildings where the new smart sensor technology could be used are schools, public buildings, office buildings, etc., but also, older sports halls, industrial buildings, warehouses. In these types of buildings it can be an advantage to have built in smart sensor technology, because it is not financially affordable to draw new extra cables. LED panels and LED high bay product with built in smart sensors for decentralized control may be advantageous in these old buildings and will be pursued by LED-TEK. Due to these considerations, it was a good idea to refrain from putting the LED smart tube into production in the reconstructed project. Installations in new buildings is normally prepared with extra wires for controlling the lightning fixtures and will therefore not be needing the Smart Sensor technology. But even here the demand for Smart sensor solutions is increasing. Especially in areas in warehouses, hall-ways and similar areas, with only occasional traffic.

LED-TEK has gained valuable information about the LED tubes that they are distributing. The photometric and endurance test results are important for registering of lighting products in the EU product database, EPREL, by September 2021. Especially the EU endurance test has not been performed for these LED tubes before and the knowledge that they passed the test both in survival factor and lumen maintenance with no problems is quite valuable.

DTU Fotonik will use many of the technological results obtained in the project, both in existing and new research and development projects and as commercial services for the Danish lighting industry.

DTU Fotonik has in the project built up long-term test facility and procedures for lifetime testing that can support Danish industry in a market where testing and verification is receiving more and more focus. Some Danish municipalities have for instance in the first rush of the introduction of LED found that lamps and luminaires did not meet the expected lifetime specified. The test facility can help Danish companies get the information needed for EPREL or large tenders where lifetime information may be needed.

The optical sensor system for monitoring over long periods of time, developed in the project has shown a resilience and robustness in measurement accuracy and data reliability that make it useful beyond this project. Currently many institutions are investing in integrative lighting also known as human centric lighting and research and development projects in these fields require robust sensors for light monitoring.

DTU participated in the revision of *IES LM-80-20 Approved Method: Measuring Luminous Flux and Color Maintenance of LED Packages, Arrays, and Modules,* using input from the project.

The measurement of spectral power distributions of LED products over time, is a valuable asset in DTUs continuing work with LED based lighting and lighting metrology such as the IEA SSL Annex and European EMPIR projects, conducted under the EU Horizon 2020 programme.

DTU has participated in an extensive review of the IEA 4E SSL Annex report on lifetime testing, *Literature Summary of Lifetime Testing of Light Emitting Diodes and LED Products* using input from this project.

https://www.iea-4e.org/ssl/news/new-iea-4e-ssl-annex-literature-review-offers-insights-into-complex-area-of-led-lifetime-testing/

6.2 Utilisation of commercial results

Since the commercial results are not as many as intended in the original project, with no production of a 0-series of the LED smart tube and no market introduction, there is little direct utilisation of commercial results from the project. The company, JensenLED, which set the original commercial objectives for the project was not able to carry this out, and had to sell out and practically close the company within the project period.

LED-TEK will continue to promote both the LED standard tubes and LED tubes with Smart sensors. LED-TEK intend to promote the test results wherever it is relevant, e.g. for customers and use it in the registration of LED products in the EU product database, EPREL. Here, lifetime in L70B50 must be reported and the companies will be held accounted for the lifetime they have entered in compliance test. Therefore, knowledge that the LED tubes will be able to pass an EU endurance compliance test is vital and valuable information for the company itself and for its customers.

Hence, the project did not yet lead to increased turnover, exports, employment and additional private investments. LED-TEK has not seen yet seen an increasing demand for LED Smart tubes. But as mentioned in pk. 6.1 the demand and sale of fixtures/luminaires with built-in Smart Sensor technology in increasing. The project results on possible energy savings with luminaire mounted light sensors will be used to investigate how and when to implement this technology in LED panels and LED high bay products for old buildings, where it is not economically viable to install extra cables. It is expected that this use of the smart sensor technology will lead to increased employment of 1-2 people and an increased turnover of 0.5 mio. Dkr over 5 years. It is not expected that it will lead to increased export.

DTU will be able to provide the EU endurance test as a service to the lighting industry, this will be done through the DOLL laboratory. It is still a very time consuming process and hence an expensive service and it will be interesting to see how large a need there will be for this service.

The LED lighting market is very competitive and fast moving. The competing solutions in the market for indoor lighting are mainly systems with a central daylight sensor in the room that controls all the light fixtures in the room. An example of such a system could be the Lutron Daylight Sensor (https://www.lutron.com/TechnicalDocumentLibrary/3683587_Daylight_Sensor_Design_and_App_Guide_sg.pdf) and there are many others. But as the simulation and analysis concludes such a system does not provide the same high energy savings, as a distributed sensor system. Other competing solutions could be individually manually dimmable light sources like the Philips Hue system. Manual control is not a suitable solution though if you want to secure energy savings since it requires humans to continuously adjust the light.

The project results have provided evidence for the lighting conditions in a storage hall with six zones and data with a resolution of minutes over two years, been used to make a simulation of the energy savings that can be achieved though light control alone, compared to normal LED tubes with same efficiency. This has been shown to give extra energy savings of 40-60%, in a storage hall with skylight windows, when having decentralized sensors that can control individual light source, or light source groups. This type of functionality will most probably in the coming years be provided by LED-TEK, not in LED tubes, but in others types of LED products, like LED panels and LED high bay luminaires, and will in that way contribute to realise energy policy objectives. These will be used in old buildings, where this decentralised light and motion control is the most economically viable solution, compared to installing new extra cables.

6.3 PhD education

No Ph.D. education was involved in the project.

7. Project conclusion and perspective

The main conclusions made in the project is that:

- energy savings of 40-60 % is achievable using LED smart tubes with daylight control instead of normal LED tubes in an industrial environment
- A 26 % higher energy saving can be achieved by using distributed light control in all zones of the analysis compared to the one with lowest energy saving
- An robust calibrated optical sensor for illuminance measurements with application limited field of view and wireless datatransfer to the illumicloud storage is possible to have running 24/7 over years with hardly any maintenance
- A zone mapping of the lighting conditions in floor level illuminance in the storage hall was achieved over 2 years with high time resolution establishing a valuable basis for analysis of daylight control systems
- The high power LED tubes survived the EU endurance test with 100 % survival factor
- The lumen maintenance of the high power LED tubes was 104 % at 3000 h
- The on/off cycling in the EU endurance test did not change the lumen maintenance compared to continuous on
- The endurance test showing that the construction of the LED tubes is thermally well constructed and robust and very good as the basis of the LED smart tube functionality in turning on and off depending on daylight level and motion/presence requiring the lighting
- The work was usable as contribution to international standardization and regulation in IES, IEA and CIE

Next steps for the developed technology is

- To determine which type of LED lighting products where it will be the most advantageous to implement the distributed light control and smart sensor technology in
- For LED-TEK to make a business plan for these LED products
- To do more investigations of how distributed light control will affect people using the buildings
- Use of obtained knowledge and optical sensors for lighting research project in e.g. integrative and circadian lighting

In perspective, it is the hope that the idea of distributed light control, having smart sensors in individual lamps/luminaires for daylight and/or motion control will get a widespread use and be implemented in LED lamps and luminaires. This will ensure that energy savings also can be achieved in old buildings where it is not economical viable to install systems that require extra cables to be installed.

8. Appendices

The homepage for the project can be accessed via: https://orbit.dtu.dk/en/projects/energy-saving-led-smart-tubes-in-intelligent-solutions and here relevant documents/publications are available.

Datasheet for LED tubes testet which are under the patent EP 2 044 362 B1: https://www.led-tek.dk/media/389478/datablad-led-jl-t8-highpower-flickerfree-serie.pdf