The role of lighting in deep energy retrofitting in European shopping malls

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Abstract
Energy retrofitting solutions applied in building envelopes of shopping centres often involves additional insulation layers on the building facade and roof as well as substituting the old windows with better performing ones. Such measures increase the thermal insulation of the envelope and reduce the energy need for heating. Analysis of 11 shopping centres in Europe reveal a lack of availability of indoor natural daylight, especially in shops and sales areas.

This paper investigates retrofitting solution for lighting in a shopping mall in Trondheim, without and with measures taken on the building envelope. Internal daylight and internal illuminance levels were measured together with detailed monitoring of energy use and indoor air quality.

Different cases were modelled to simulate the use patterns and control strategies of artificial lighting in the shopping centres by considering occupancy hours and type of activity (luminance levels), in order to cover different possible combinations, which are used in the energy and daylight simulations.

Existing conditions of a representative shopping centre (pre-retrofitting) were modelled based on the energy use measurements, and energy and daylighting simulations were performed. Combinations of use pattern and facade variables were used for the daylight and energy simulations in the retrofitted shopping centres to evaluate the influence on the electricity use of lighting, and heating and cooling energy needs of the combinations of the scenarios. There is a trade-off, which is quantified in terms of reduction in electricity use and increase in heating demand. Besides the straight forward end energy use savings (electricity), lighting retrofitting has implications for heating and cooling end energy use and primary energy savings. Shopping centre managers need to collaborate closely with shop owners/managers on energy retrofitting measures if the full potential is to be enabled.

Introduction
Several researchers, mostly organized through international organizations (e.g. IEA) have put significant efforts towards energy efficiency improvement in existing buildings (Zhenjun et al., 2012). In the past several years, the International Energy Agency (IEA) launched e.g. Annex 45 titled 'Energy efficient electric lighting for buildings' and Task 50 'Advanced Lighting for Retrofitting Buildings' (Dubois et al. 2015). However, from 21 case studies from 10 countries only one case study focused on Retail buildings (Dubois et al. 2016). There is a strong focus on office and educational buildings, which is also reflected in the literature (Voss et al. 2006). Dascalaki & Santamouris (2002) summarize work done in the OFFICE project and conclude that:

- The potential for energy savings depends significantly on the building type; more compact building shapes demand more energy for electric lighting and thus present a higher energy saving potential than other building types.
- It is necessary to look at energy savings in a holistic way (for the whole building) since electric lighting reductions normally entail an increase in heating loads (and reduction in cooling), which can make lighting retrofit measures less cost effective considering all other end-uses.

One of the most effective approaches to minimize energy use in the non-residential sectors is by using occupancy based lighting control systems (IEA, 2006; Garg & Bansal, 2000; Galasiu et al., 2007). As a result of occupants not turning the lights off when they no longer need them, more energy is spent on non-working hours than during scheduled time as emphasized by Masoso & Grobler (2010). Therefore a new collaborative research project was launched in 2013. The CommONEnergy project aims to transform shopping centres into lighthouses of energy efficiency.

Shopping centres are not interchangeable with other kinds of complex buildings, such as office blocks, hospitals or schools (ICSC 2008; Stensson 2014; Coleman 2006). Their form, function, usage, and users provide shopping centres with a particular character. Both energy load profiles and final uses are not comparable with other building categories, (e.g. very high internal loads) which has implications for energy use (Coleman 2006; Stensson 2014; Woods et al. 2015). To support the understanding of what causes the main inefficiencies in energy usage and enable the development of the best solutions, a definition of shopping centres was developed (Bointner et al. 2014). The definition describes a shopping centre as "a formation of one or more retail buildings comprising units and 'communal' areas which are planned and managed as a single entity related in its location, size and type of shops to the trade area that it serves" (Bointner et al., 2014). The definition gives an indication of the main form and function in shopping centres. In addition, location, type of development, the size and gross leasable area (GLA), the type of anchor stores and the trip purpose are all aspects that have been used to indicate the needs that a shopping centre serves within the social and physical context (Woods et al. 2015a; Woods et al. 2015b;).

Commonenergy is a project with 23 partners that studies comprehensive retrofit solutions sets to save energy and promote high Indoor environmental quality in shopping centres, as well as the optimal environmental conditions for displaying and selling merchandise. Comparing to the pre-retrofit conditions, the project aimed to achieve a 75 % reduction of energy demand, power peak shaving, a 50 % increased share of energy used from Renewable Energy Sources (RES) compared to a base-case (renewables share so far), and an improved Indoor Environmental Quality (IEQ). The research was based on the demand for a comprehensive approach for the development of a retrofitting package for shopping centres, taking into account the specific needs of the building, such as indoor conditions, complex energy flows and the lack of standard energy intensity performance indicators (Bointner et al. 2014; Haase et al. 2015a; Haase et al. 2015b).

The analysis of 11 representative shopping centres in Europe reveal a lack of availability of indoor natural daylight, especially in shops and sales areas (Woods et al. 2015a; Haase et al. 2015b)). The shopping centres that were analysed vary in size and energy use. Figure 1 shows the share of gross leasable areas in the different reference buildings. It can be seen from Figure 1 that common areas cover areas between 12 % and 21 % in the reference shopping centres. On average, 15 % of the gross leasable area (GLA) is used by common (and service) areas. Accordingly, retrofitting measures that focus only on common areas will have a minor effect on the total energy use in shopping centres.

Objectives

The scope of this paper is to investigate the consequences on heating and cooling energy consumption and electricity use for lighting when a novel retrofitting solution is applied to a Norwegian shopping centre.

Methodology

Measurements in a shopping centre in Trondheim of internal daylight and internal illuminance levels together with detailed monitoring of energy use and indoor air quality, were collected by use of sensors and an intelligent Building Energy Management system including data loggers and cloud storage. The data was collected every six minutes over a time range of 6 months.

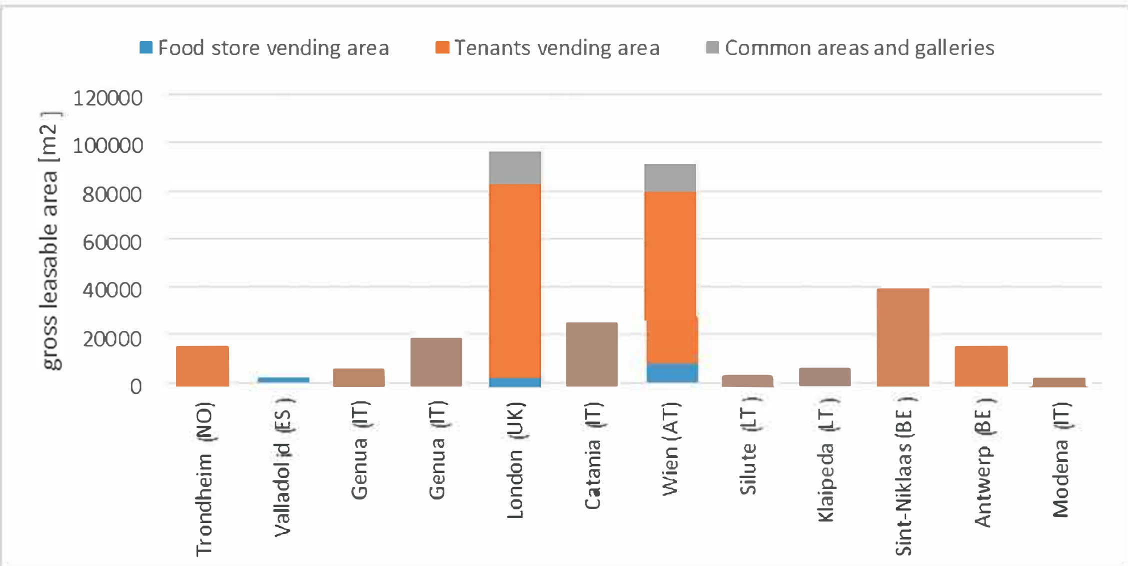

Figure 1. Gross leasable areas (GLA) of the different reference buildings.

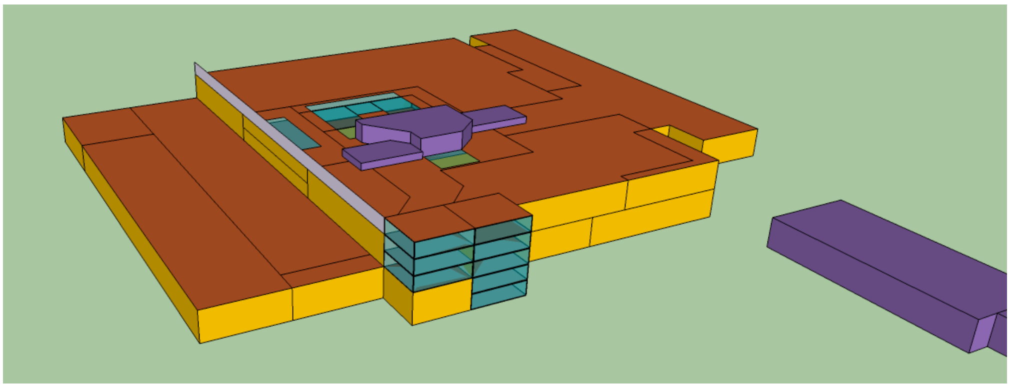

Figure 2. Model representation in sktechup of the shopping centre in Trondheim, Norway.

Table 1. Lighting control strategy.

case	Area	no. of luminaires	control strategy	power p. luminaire
		–	–	[W]
(0)	Common area + shops	43	constantly on during op. hours	70
(1)	Common area	57	+ PREP hours + day/night milieu	27
(2)	Shop – not daylit zone	31		32
(3)	Shop – daylit zone	26	+ light tubes	21

Two different cases were developed to investigate the effect of use patterns and control strategies of artificial lighting in the shopping centre by considering occupancy hours and type of activity (illuminance levels). The building was modelled in TRNSYS according to the plans and architectural drawings. A sketchup model was developed that needed to be simplified as shown in Figure 2. The functional units in the shopping mall were divided into common areas, shops, and others (Haase et al. 2015). Existing conditions of the shopping centre (pre-retrofitting) were modelled in TRNSYS based on the energy use measurements, and energy and daylighting simulations were performed. Combinations of use pattern scenarios and facade variables were used for the daylight and energy simulations in the retrofitted shopping centres to evaluate the influence on the electricity use of lighting and energy use of the combinations of the scenarios.

Results

LED LIGHTING CONCEPT

Description of the different cases:

- Case (0): base case of the situation without retrofitting
- Case (1) new LED lighting installed in the common areas
- Case (2) new LED lighting installed in the common areas and in the shop
- Case (3) additional installation of light pipes.

Cases 1 and 2 are investigates the installation of new LED lighting with reduced intensity in the preparation hours (PREP), 2 hours in the morning (from 07:00 until 09:00) and night milieu, 5 hours in the afternoon (from 17:00 until 22:00). Case 3 investigates an installation of 3 light tubes that daylit a 100 m^2 demonstration shop on the first floor of the shopping centre in Trondheim. In praxis this means that 3 light pipes is enough to light up 80 % of the shop area (equal to 3 light pipes/80 m^2 =0,04 light pipes/m^2). Each case is also described in (Haase et al. 2017, Ampenberger et al 2017). It can be seen that the resulting power per luminaire is reduced for cases (1) to (3) compared to case (0) as shown in Table 1. Daylight can further reduce required power per luminaire to 21 W (case 3).

LIGHT TUBES SOLUTIONS

The demonstration shop area was 100 m^2 (including 15 m^2 storage). The diameter of each light tube is 1,000 mm. Rooftop domes were placed on top of each light tube to provide air and water tightness. For case (3) it was assumed that 3 light tubes per 100 m^2 were installed in the shops on the first floor. They bring daylight to 80 m^2 of the shop (80 %).

With the installation of three light tubes per 80 m^2 in case 3 it is possible to reduce the artificial lighting according to daylight illuminance. This can be seen in Table 2 which shows the results of the nominal power for the demonstration shop area in the Trondheim shopping centre. It can be seen that cases (1) to (3) reduce nominal power installed during opening hours, during preparation (PREP) hours and during night milieu hours.

ENERGY IMPLICATIONS

The shopping centre is equipped with a heat pump (for peaks) and a district heating system. The implications of the installed power reductions of the cases (1) to (3) compared to case (0) are shown in Table 3. It can be seen that the mean specific power demand per area is reduced from 39.8 W/m^2 in case 0, to 16.5 W/m^2 in case 1, to 15.2 W/m^2 in case 2 and to 9.6 W/m^2

in case 3, when the luminous flux is reduced to 1. 28 klm/m² and 1.23 klm/m², respectively. The implications of the different lighting retrofitting measures were then applied to the whole shopping centre. The cases were applied to two different areas and resulting energy implications calculated. First, the lighting retrofitting case (1) was applied to the common areas. Electricity savings were determined in primary energy (PE). Heating and cooling implications were determined. Secondly, the lighting retrofitting cases (1) and (2) were applied to the shop areas. Electricity savings were determined in primary energy (PE). Heating and cooling implications were determined.

The results from energy simulations can be divided into electricity use, heating and cooling needs. Here, a focus was put on the lighting retrofitting measures, not on appliances nor on ventilation. This means that ventilation remains the same for all cases.

Heating and cooling implications

Table 4 shows the heating and cooling implications. It can be seen that cooling demand (or consumption?) reduces from 20.1 kWh/(m² a) in case 0 to 4 kWh/(m² a) for cases 1 and 2. The need for heating increases from 49.5 kWh/(m² a) in case 0 to 70.4 kWh/(m² a) for case 1 and 84.3 kWh/(m² a) for case 2. Together with electricity reduction from lighting the sum also reduces from 206.8 kWh/(m² a) in case 0 to 124.4 kWh/(m² a) for case 1 and 119.5 kWh/(m² a) for case 2.

The changes are small when looking at the results for the common areas. Energy use for cooling reduces insignificantly from 20.1 kWh/(m² a) (case (0)) to 19.4 kWh/(m² a) for cases (1). Energy use for heating increases from 49.5 kWh/(m² a) (case (0)) to 58.1 kWh/(m² a) for case (2).

Primary energy reductions

Figure 3 shows the primary energy implications for Trondheim applying the cases (1) and (2) to different parts of the shopping centre. Primary energy factors of 2.5 kWh_{PE}/kWh_{el} for electricity and 0.75 $kWh_{PE}/kWh_{distr.heat}$ for district heating were used.

Primary energy (PE) use for the whole shopping centre is 712 kWh_{PE}/(m² a) with 110 kWh_{PE}/(m² a) for ventilation (ventilation remains the same and is thus not shown in Figure 4). Primary energy (PE) use for case (0) for lighting is 343 kWh_{PE}/(m² a), for appliances 141 kWh_{PE}/(m² a), for heating 67.2 kWh_{PE}/(m² a), and for cooling 50 kWh_{PE}/(m² a).

Primary energy (PE) use for lighting can be reduced by 39 kWh_{PE}/(m² a) (5.5 % for case (1)) if applied to the common

Table 2. Lighting power installed.

case	Area	power per luminaire		nominal power		
		during opening hours	during PREP hours	during opening hours	during PREP hours	during night milieu
		[W]	[W]	[kW]	[kW]	[kW]
(0)	Common area + shops		–	3.39	–	–
(1)	Common area	27	19	1.54	1.08	1.08
(2)	Shop – not daylit zone	32	22.6	1	0.7	0.7
(3)	Shop – daylit zone	21	14.6	0.55	0.38	0.38

Table 3. Lighting power installed.

case	Area	Mean specific power demand per area	Specific luminous flux per area
		[W/m²]	[klm/m²]
(0)	Common area + shops	39.8	2.06
(1)	Common area	16.5	1.28
(2)	Shop – not daylit zone	15.2	1.23
(3)	Shop – daylit zone	9.6	1.23

Table 4. Heating and cooling use in kWh/(m² a).

case	Area	Lighting	Heating	Cooling	Sum
		kWh/(m² a)	kWh/(m² a)	kWh/(m² a)	kWh/(m² a)
(0)	Common area + shops	137.3	49.5	20.1	206.8
(1)	Common area	119.4	58.1	19.4	196.9
(2)	Common area + shops	50	70.4	4.0	124.4
(3)	Common area + shops on first floor	31.2	84.3	4.0	119.5

areas. These are the typical areas, which are managed and maintained by centre managers directly.

Applying lighting retrofitting case (1) to all areas (cma and shops) results in PE savings of 246 $kWh_{PE}/(m^2\ a)$ (34.6 % for case (1)). If case (2) was applied to all suitable shops (all shops on the first floor) PE savings of 282 $kWh_{PE}/(m^2\ a)$ (39.6 %) can be reached. Table 5 summarizes the results as PE savings (compared to case (0)). It can be seen that the differences for the sums is small; case (1) saves almost 40 % PE while case (29 saves 42 % PE. The differences are larger whan looking at electricity and heating. Here, case (1) saves 65 % PE for lighting and increases PE for heating by 42 % while case (2) saves 77 % PE for lighting and increases PE for heating by 70 % while PE for cooling is reduced by 80 % for both cases. While only a small amount of PE is used by the cooling system, it has implications on the operational level. There is no additional cooling system for both cases ((1) and (2)) in the renovated situation required, but adjustments to the heating system are needed.

Discussion

Together with electricity reduction from lighting the sum from lighting, heating and cooling also reduces. But final energy use for heating increases. PE savings of 39.8 % were possible with lighting retrofitting in common areas and shop areas. However, lighting retrofitting of shop areas is the responsibility of the shop owner/manager. It requires further engagement of these stakeholders to effectively implement lighting retrofitting solutions. These solutions are saving electricity (end energy use) but also influence heating and cooling end energy use.

The highest heating energy use is for case (3) (to 84 $kWh/(m^2a)$). Even if the total energy use is minimized, an increase in heating demand requires additional investment in heating system upgrade. Other measures should be applied in the next step that reduce energy use for heating to complement the lighting retrofitting strategy.

The consequences for existing window and roof structures needs to be further investigated in order to be able to give the centre and shop managers a basis for decision making on refurbishment investments.

Conclusions

Existing conditions of a Norwegian shopping centre (pre-retrofitting) were modelled based on the energy use measurements and energy and daylighting simulation were performed. Combinations of use pattern scenarios and facade variables were used for the daylight and energy simulations in the retrofitted shopping centres to evaluate the influence on the electricity use of lighting and energy use of the combinations of the scenarios.

The work that formed the basis for this paper investigated into the consequences on energy consumption and electricity

Table 5. Primary energy savings for lighting, heating and cooling. Percentage of case 0.

Case	area	Lighting	Heating	Cooling	Sum
(0)	Common area + shops	0.0 %	0.0 %	0.0 %	0.0 %
(1)	Common area	13.0 %	-17.4 %	3.5 %	4.8 %
(2)	Common area + shops	63.6 %	-42.2 %	80.1 %	39.8 %
(3)	Common area + shops on first floor	77.3 %	-70.3 %	80.1 %	42.2 %

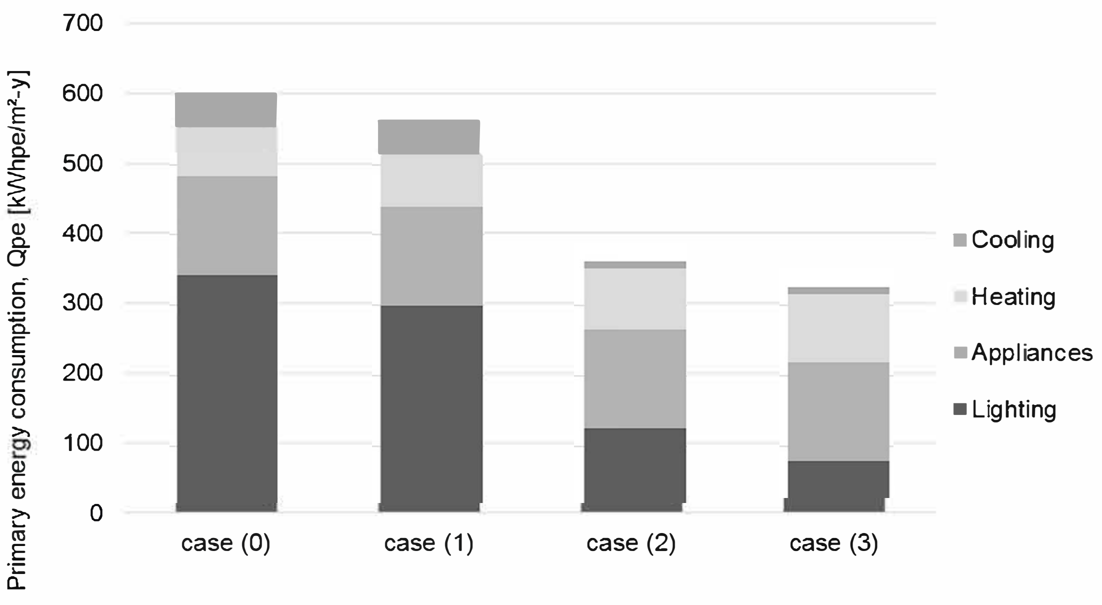

Figure 3. Primary energy use in the shopping centre of the four investigated cases.

use for lighting that a novel retrofitting measures has when applied to a typical shopping centre. Applying lighting retrofitting results in PE reduction of up to 40 %. The end energy use for lighting, heating and cooling also reduces. However, while end energy use for lighting and cooling reduces, the end energy use for heating increases.

There is a trade-off, between reduced electricity use for lighting and demand for cooling, towards increased heating demand. However, the findings in Table 5 shows that if using a primary energy factor of 2.5 for electricity, reduced electricity demand will reduce the total primary energy use, despite the increased heat demand. Case (2), which applies light tubes to the existing roof structure, performs better when looking at PE savings.

Shopping centre managers are normally responsible providing heating (and often cooling, or at least cooling energy) to the shops. Lighting is usually in the responsibility of (each) shop owner/manager. The implications of lighting retrofitting on heating and cooling (besides the end energy use savings) make the application complicated in shopping centres. Modelling and simulation of a shopping centre can help to understand the holistic consequences of single energy retrofitting measures. Besides the straight forward end energy use savings (electricity), lighting retrofitting has implications for heating and cooling end energy use and primary energy savings. Shopping centre managers need to collaborate closely with shop owners/managers on energy retrofitting measures if the full potential is envisioned to be applied.

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