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Life cycle assessment of light-emitting diode downlight luminaire – a case study

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Abstract

Purpose Light-emitting diode (LED) technology is increasingly being used for general lighting. Thus, it is timely to study the environmental impacts of the LED products. No life cycle assessments (LCA) of recessed LED downlight luminaires exist in the literature, and only a few assessments of any type of LED light source (component, lamp, luminaire) are available.

Methods The LCA of a recessed LED downlight luminaire was conducted by using the data from the luminaire manufacturer, laboratory measurements, industry experts and literature. The assessment was conducted using SimaPro LCA software. Ecoinvent and European Reference Life Cycle Database were used as databases of the impact assessment. The LCA included a range of environmental impacts in order to obtain a broad overview. The functional unit of the LCA was one luminaire used for 50 000 h. In addition, the sensitivity of the environmental impacts to the life was studied by assessing the LED downlight luminaire of 36 000 h life.

Results and discussion The environmental impacts of the LED luminaire were mostly dominated by the energy consumption in the use stage. However, the manufacturing stage caused the majority of impacts in the categories of the hazardous waste and non-hazardous waste. The environmental impacts of the manufacturing were mainly due to the driver, LED array and aluminium parts. The installation, transport and end-of-life had nearly no effect on the total life-cycle impacts. The life cycle environmental impacts were found out to be sensitive to the life of the luminaire: The life of 50 000 h resulted on the average to 17 % lower environmental impacts compared to a 36 000 h life.

Conclusions and recommendations The case study showed that the environmental impacts of the LED downlight luminaire were dominated by the use-stage energy consumption. Luminous efficacy is thus a relatively appropriate environmental indicator of the luminaire. As LED technology possesses generally higher luminous efficacy compared to conventional light sources, the LED luminaire is considered to represent an environmentally friendly lighting product. However, due to the data gaps, it is needed to produce more detailed data on the LED product manufacturing and its environmental impacts. The environmental impacts of different LED products need to be analysed in order to be able to precisely compare the LED technology to the conventional lighting technologies.

Keywords: life cycle assessment, light-emitting diode, luminaire, lighting, environmental impact, light source

1. Introduction

1 It is estimated that lighting consumes approximately 19 % of the global electricity production (IEA 2006).
2 Globally, the electrical lighting is provided mainly (62 %) by fluorescent lighting, including fluorescent and
3 compact fluorescent lamps (IEA 2006). In contrast, the share of light-emitting diode (LED) in general lighting is
4 low; LED lighting was estimated to cover 6.2 % of the general lighting in the European Union in 2010 (EC
5 2011). However, the market penetration of LED technology is rapidly increasing not only in the decorative
6 lighting of coloured, usually low-power applications, but also in general lighting.
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9 The LED light sources represent a relatively new technology. In addition to the indicator and decorative lighting,
10 there are LED lamps and luminaires on the market that possess sufficient luminous flux to be used in general
11 lighting and even in high-power outdoor lighting. The challenges in the heat transfer from the chip through the
12 heat sink have hindered the wider use of the LED technology. Efficient heat transfer is essential in order to slow
13 depreciation of the luminous flux in LED light sources and thus realize long life.
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15 The environmental aspects of LED products have not been studied exhaustively, yet some studies exist. Lim et
16 al. (2011) studied the material contents of indicator LED components of different colours by leachability tests.
17 However, it concerns only the LED components of through-hole technology, and not the LED lamp or luminaire
18 as a whole. Dale et al. (2011) studied four different streetlight technologies, one of which was an LED luminaire.
19 The study compared one-to-one replacement of high pressure sodium lamp luminaire to the metal halide,
20 induction or LED lamp luminaire. It did not take into account the luminous flux or the standards and
21 recommendations for street lighting. In addition, the ballasts and drivers were estimated to be similar and thus
22 excluded from the assessment. The LED luminaire was found out to have the lowest environmental impacts that
23 were similar with the ones of the induction lamp luminaire. Navigant consulting (2009) examined several
24 energy-efficient light sources including an integrally-ballasted LED lamp (12 W, 720 lm) and an LED luminaire
25 (18 W, 1170 lm). The life-cycle environmental impacts of an LED lamp have also been compared to
26 incandescent and compact fluorescent lamps (CFL) (Osram 2009, Quirk 2009). The conclusion of the
27 assessments are generally that LED and CFL lamps possess roughly the environmental impacts of the same scale
28 and that the future LED lamp will be more environmentally friendly than the CFL, since no major technological
29 development are expected in the CFL technology.
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33 The environmental performance of the light source is dependent on the luminous efficacy if the analysis uses a
34 proper functional unit taking into account the amount of light produced. The luminous efficacy of incandescent
35 lamp is low, typically 10-15 lm/W, while the one of CFL ranges approximately between 40 and 70 lm/W
36 including the ballast, and fluorescent lamps (T5) up to approximately 100 lm/W including the ballast. The
37 luminous efficacy of LED lamps has a wide range, approximately between 20-120 lm/W (Aalto University
38 2010). The LED chip luminous efficacy has well exceeded 200 lm/W in laboratories. In contrast to the LED
39 technology, no major improvements are expected in the development of the conventional light source
40 technologies such as incandescent or fluorescent lamp technology. In addition, the lamp technologies of low
41 energy efficiency are being banned in many regions, e.g., the inefficient incandescent lamps and high pressure
42 mercury lamps in the European Union.
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45 Currently, there are LED lamps and luminaires of varying properties available on the market. Notable
46 differences are found in the properties among LED light sources concerning, e.g., the luminous flux, electrical
47 properties such as harmonic distortion, colour temperature, colour rendering, colour shift and lumen
48 maintenance.
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50 This study introduces the life cycle assessment (LCA) of an LED luminaire. It is a case study of one type of
51 recessed downlight luminaire and does not represent the LED technology as a whole. Yet, it is an exemplary
52 case. The use-stage energy consumption was found out to be the most significant environmental aspect in the life
53 cycle of the LED luminaire. The manufacturing stage is dominated by the environmental impacts of the
54 manufacturing of the driver, LED array and aluminium parts. The end-of-life (EoL) scenario has an insignificant
55 impact on the LCA. The analysis is somewhat sensitive to the life estimate of the product. More LCAs of LED
56 products are needed in order to study profoundly the environmental impacts of the technology and the wide
57 product range.
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2. Life cycle assessment of light-emitting diode luminaire

The environmental impacts of an LED luminaire were estimated on the basis of an LCA. The LCA was conducted for an LED downlight luminaire in Figure 1. The LED luminaire in question is a high-quality luminaire used in commercial and retail applications, in which it is intended to replace downlight luminaire equipped with two CFLs. The nominal electrical power of the LED luminaire is 19 W. The product contains the driver and the LED luminaire including all its parts, such as the heatsink, reflector, high-power blue LED components on a circuit board, and a “remote phosphor” plastic diffuser, whose external surface is coated with a thin layer of luminophores. The LCA is conducted according to the international standards ISO 14040 (2006) and ISO 14044 (2006), and a French standard NF P01-010 (2004). The SimaPro version 7.3.2 was used as the LCA software (PRé Consultants).

2.1. Goal and scope definition

The goal of this LCA is to study the environmental impacts of an LED downlight luminaire and to determine the life cycle stages and material and energy inputs that are the most significant. In addition, it is determined how sensitive the environmental impacts are to the life of the luminaire.

The LCA includes the manufacturing, transport, installation, use and EoL stages (Figure 2). The system boundaries exclude the lighting, heating and cleaning of the factories; administrative work; transport of the employees; tool manufacturing; infrastructure; and transport infrastructure, such as building and maintenance of roads. The study excluded also the inputs that represented less than 2 % of the total weight of the product and for which there were not life cycle inventory available, according to the rules of the French standard NF P01-010.

The functional unit is the use of the 19 W LED downlight luminaire including the driver during 50 000 h and producing 1140 lm of light with colour rendering index R_a of about 80. All the electrical and photometric characteristics were measured by the CSTB lighting laboratory (Martinsons 2009a, 2010), and the life is based on the information from the manufacturer, since life tests are still in progress at CSTB. The measured luminous efficacy is about 60 lm/W.

Since the life of the luminaire is a crucial factor in the LCA, its impact is studied more profoundly. The life of the LED products is allegedly long but there are concerns regarding its realization. The life of the LED downlight luminaire is 50 000 h according to the manufacturer. A life of 50 000 h is a somewhat general approximation for LED luminaires but it is not possible to carry out burning tests of such a long life. The life of the ballast is considered in the LCA to be the same as the life of the luminaire, since it is sold as one unit and the ballast will be replaced together with the rest of the luminaire. At the end of the operating life, the luminaire is expected to provide less than 70 % of initial luminous flux taking into account both the lumen depreciation and product failures.

The life of 50 000 h is used as a base case scenario in the LCA. The base case is compared to the lives of 36 000 h. In case of a shorter life, the share of the manufacturing efforts increases in the total life cycle perspective. 36 000 h life was chosen on the basis of the LM-80 (IESNA 2008) method. The method states that the life of the LED packages and modules shall be estimated based on a burning test of a minimum of 6 000 h. It is recommended to extrapolate the life of the LED package or module based on the burning test only up to *six times* the test period, i.e., in the case of 6 000 h test, until 36 000 h. It is noted that LM-80 does not apply to LED luminaires as a whole but it was used, nevertheless, due to the lack of a specific method for LED luminaires.

In addition to the life of the luminaire, the annual environmental impacts are dependent on the use scenario. The annual operating hours are not included in the LCA but only the total life is considered. However, the annual environmental impacts depend on the annual operating hours. The annual operating hours vary according to the use of the space, but are approximately, e.g., 2 500 h per year in offices and 5 000 h per year in hotels and retail facilities (EN 15193).

2.2. Life cycle inventory analysis

Manufacturing

1 The manufacturing stage comprises the raw material acquisition of all parts of the luminaire installed in the
2 beginning of the operating life. The manufacturing of the replacement luminaires, in case of the shorter operating
3 life than 50 000 h, is modelled in the use stage according to the NF P01-010 (2004).

4 Table 1 lists the material and process inputs of the LED downlight luminaire manufacturing. The driver data was
5 retrieved by dismantling the driver and identifying the components. All driver parts include an additional 2 %
6 mass to take into account the material losses of the manufacturing. The printed circuit board (PCB) is modelled
7 as 2-sided board that includes the mounting processes (50 % through-hole technology (THT) and 50 % as
8 surface-mount technology (SMT)). THT components were weighed, while the weight data of the SMT
9 components was retrieved from component datasheets and ZVEI documents (ZVEI 2012). The remote phosphor
10 has recently been the subject of a French Luminosurf research project. In this project, CSTB conducted LCAs on
11 several types of organic and inorganic luminophores used in LED lighting (Pradal et al. 2012, Martinsons
12 2009b). The luminaire assembly process is modelled on the basis of the energy consumption provided by the
13 luminaire manufacturer: approximately 0.03 kWh of electricity per luminaire. The amount of electricity covers
14 only the assembly process and not the other energy consumption of the luminaire factory.

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17 The LED components were modelled as 5 mm LED components for information and communication technology
18 found in the ecoinvent database in which the particular data was from year 2007 (Ecoinvent 2010). However, it
19 is estimated that the diode in the database, a THT component, results to low environmental impacts compared to
20 the actual SMT LED component. Thus, on the basis of the estimations by industry experts, the weight of the
21 SMT LEDs is multiplied by a factor of *five* in order to take into account the underestimation in the component
22 data. Yet, it is acknowledged that a more accurate and up-to-date life cycle data is needed regarding the LED
23 components used currently in general lighting.

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26 Transport of parts is included in each part accordingly, a total of approximately 2 tkm by lorry and 12 tkm by
27 transoceanic freight. Likewise, packaging is taken into account and modelled in each part. Packaging is modelled
28 mainly as cardboard that accounts for approximately 10 % of the weight of the product parts if precise data was
29 unavailable. The cardboard used in the packaging of the luminaire parts is estimated to total 114 g and the
30 package of the final product 210 g. The waste treatment in the manufacturing stage covers the transport and
31 recycling of the cardboard packages.

32 33 34 *Transport*

35 Transport stage includes the transport from the manufacturer site to the place it is used. Transport data was
36 gathered from the luminaire manufacturer, and when such data was not available, the default scenarios for the
37 product environmental profile (PEP) (Association P.E.P. 2011) were used as reference. In PEP, the global
38 transport is estimated to be 19 000 km by ship and 1 000 km by lorry, the intercontinental transport 3 500 km by
39 lorry, and local transport 1 000 km by lorry.

40 41 42 *Installation*

43 The installation of the luminaire considers the transport and the final storage of the package materials. The
44 transport is modelled as 30 km by lorry. The final waste disposal is modelled as municipal solid waste
45 deposition.

46 47 48 *Use*

49 The use of the luminaire is modelled on the basis of the energy consumption. The downlight luminaire consumes
50 19 W per hour. The French average mix is used for electricity production. The French electricity is modelled to
51 be produced by nuclear power (77 %), hydropower (12 %), coal (4 %), natural gas (3 %), and oil (1 %), and
52 imported (2 %) (Ecoinvent 2010).

53 54 55 *End-of-Life*

56 On the basis of the information from the French lamp recycling organization Recylum, two EoL scenarios of the
57 LED luminaire were created: current and prospective treatment scenarios. The current scenario is estimated to be
58 95 % of landfill and 5 % of recycling treatment, while the prospective scenario includes 40 % of landfill and 60
59 % of recycling treatment. The landfill disposal takes into account the transport of the waste and the deposition on
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the landfill. The recycling treatment includes the transport of the product from the point of use to the collection point and further to the storage centre and finally to the treatment centre. The recycling treatment contains also the shredding process and separation of the fractions, the transport of the fractions, and their recycling and disposal.

2.3. Life cycle impact assessment

The life cycle impact assessment (LCIA) introduces the environmental impact categories and calculation methods used in the LCA. Ecoinvent and European Reference Life cycle Database were used as databases in the LCIA (Ecoinvent 2010; EC, JRC 2008). This assessment uses the MatFrance method, version 2.03, that is based on a French standard NF P01-010 (2004) and AIMCC (2009). The NF P01-010 is not compulsory but it is widely used in the environmental assessments in the building sector in France. The environmental impact categories are introduced in Table 2. It is mainly based on CML 2001 method (Guinée et al. 2002) but contains some differences: e.g., the photochemical ozone creation potential takes into account only the hydrocarbons (NF P01-010 2004).

Four scenarios of the product system were chosen to analyse the impact of the product life and the EoL scenario.

- 1) luminaire life 36 000 h (2 products needed during 50 000 h), current recycling scenario in the EoL
- 2) luminaire life 36 000 h (2 products needed during 50 000 h), prospective recycling scenario in the EoL
- 3) luminaire life 50 000 h (1 product needed during 50 000 h), current recycling scenario in the EoL
- 4) luminaire life 50 000 h (1 product needed during 50 000 h), prospective recycling scenario in the EoL

3. Results

The environmental impacts of the manufacturing of an LED downlight luminaire were divided between the driver, LED package, aluminium parts, remote phosphor, luminaire assembly process, waste treatment of the packaging materials, and other materials (Figure 3). The LED components and the circuit board they are attached to, i.e., the LED array, accounted for 3 % of the total weight of the luminaire, while their environmental impact ranged between 4 % and 50 % depending on the impact category. The aluminium parts, such as the heatsink, accounted for 11-42 % of the environmental impacts. The environmental impacts of the driver ranged between 19 % and 66 %. The PCB of the driver has notable share in most environmental impact categories, but otherwise the environmental impacts of the driver are scattered across a number of parts. The most critical parts of the driver are the electrolyte capacitors in inert waste and ozone depletion, unspecified capacitors in water pollution and photochemical ozone creation, steel in water consumption, and glass diodes in photochemical ozone creation and hazardous waste.

The comparison in Figure 4 presents two cases of life of the product (36 000 h, and the base case of 50 000 h) and two EoL cases (actual and prospective). Due to the lower manufacturing efforts, the environmental impacts of the base case were 1 to 44 % (17 % on the average) lower than the ones of the case of 36 000 h. The total life-cycle environmental impacts were almost independent from the EoL scenario. In the base case, the total life cycle primary energy consumption was approximately 13 070 MJ and GWP 112 kg CO₂ per the functional unit with either of the EoL scenarios.

Figure 5 shows the environmental impacts of the life cycle divided into manufacturing, transport, installation, and use phase including energy consumption and the manufacturing and transport of the replacement luminaires. Only one luminaire of 50 000 h life is needed for the functional unit (Figure 5a), while two products of 36 000 h life are needed to provide light during 50 000 h (Figure 5b). The share of the manufacturing of the initial product and the replacement products accounted for up to 88 % and 33 % on the average of the life cycle impacts.

Uncertainties

Despite the efforts put in this LCA case, uncertainties and data gaps exist in the assessment. It was not possible to model all inputs of the luminaire life cycle or to obtain representative data of each input. There was no life cycle data available on the LED chip used in general lighting but it was estimated on the basis of an indicator LED. The environmental impacts are somewhat sensitive to the life of the luminaire. In addition, this LCA case study concerns only one example of LED downlight luminaire, and the LED luminaire product range is vast.

4. Discussion

The environmental impacts of the LED luminaire vary by environmental category. However, the use-stage energy consumption was found out to account for the majority of the environmental impacts in all impact categories except for the non-hazardous and hazardous waste categories. In these two categories, the manufacturing accounted for 79 % and 52 %, of the life cycle impacts, respectively. The high percentages of manufacturing in these waste categories are mainly due to the driver and aluminium parts. The EoL had very little to no effect on the total life cycle impacts due to the dominance of use and manufacturing stages. Yet, the benefits of proper recycling of the LED luminaire are recommended to be subjected to a more profound study.

The environmental impacts of the manufacturing stage are divided mainly between the LED driver, LED array and aluminium parts, which cover together over 80 % of the manufacturing impacts in all impact category. However, there is uncertainty in the LCI data of the LED component: The LCA was conducted using an estimation of an indicator LED to correspond to the LED component by a weight factor of five. Contradictory information has been published on the correlation between the environmental impacts of the indicator LED and a high-power LED component: A US DOE (2012b) report collects thoroughly the material and energy inputs of the manufacturing processes of an LED. It states that the environmental impacts of a high-power LED component represent approximately 94.5 % lower environmental impacts than the 5 mm indicator LED in the ecoinvent database. However, while the US DOE report compared the LED components on the basis of the luminous flux (4 lm to 100 lm), the LCA on the LED downlight luminaire considered the weight of the component, not the luminous flux, as the ecoinvent data was available on weight basis. With these notably different results and methods of comparison, it is clear that more studies and data are needed in order to conclude the environmental impacts of LED products, whether in terms of the weight or luminous flux of the LED component.

The manufacturing efforts of the LED product cannot be neglected in an LCA, since it is implied that the manufacturing may account for a notable share of the environmental impacts. US DOE (2012a) study estimates the manufacturing process energy consumption to range between 0.1 % and 27 % of the total life-cycle energy consumption. US DOE (2012b) report calculated that the raw materials used in manufacturing caused 16.8 % of the total life-cycle impacts on the average.

The life of the LED luminaire affects the environmental impacts and their division between the life-cycle stages. The luminaire of the nominal life of 50 000 h causes approximately 17 % lower total environmental impacts compared to the case in which the luminaire had life of 36 000 h. The manufacturing of the LED luminaire causes 23 % of the life cycle impacts in the case of 50 000 h life, while the share of the manufacturing of the initial and replacement products is increased to 33 % in the case of 36 000 h life. Yet, there is significant variation in the sensitivity to the life among the impact categories.

The life cycle of the luminaire resulted to primary energy consumption of 13 070 MJ and GWP of 112 kg CO₂ per functional unit (50 000 h use of the luminaire producing 1140 lm). Several previous LCAs of light sources use lumenhours as the functional unit. The LED downlight consumed approximately 230 MJ primary energy and caused 2,0 kg CO₂ emissions per 1 Mlmh.

Such an LED downlight luminaire has not been subjected to an LCA before. It is not possible to accurately compare this LCA to the ones of LED lamps or LED luminaires of different purposes and LCA boundaries. However, the LCA results show that the use phase energy consumption is dominant but also that the manufacturing stage cannot be neglected. More research is needed in order to study the environmental impacts of the wide range of the LED technology.

5. Conclusions

The environmental impacts of the LED downlight luminaire in the case study were generally dominated by the energy consumption in the use stage. Thus, it confirms the use of luminous efficacy of a light source as an environmental indicator. However, the results show that the manufacturing efforts cannot be neglected in the

LCA of the LED luminaire. Yet, it is acknowledged that there are uncertainties in the LCA calculations, notably in the modelling of the LED components.

The importance of the manufacturing stage will be further increased when the energy production is shifted to the less-polluting energy production. In that case, the significance of the EoL stage may also increase. The results showed that the EoL treatment had nearly no impact from the life cycle point of view. Yet, the recycling of the LED luminaire may increase along with the increase of the collection and treatment targets of the waste electrical and electronic equipment.

Further studies are suggested to include a wide range of LED products. In case of comparing light sources of different shapes and sizes, the functional unit needs to be appropriate. It is also advised to analyse the sensitivity of the LCA to the used energy source. In addition, the future sustainability studies may consider the fast increase of the luminous flux and decrease of the costs of the LED products.

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Tables

Part	Raw material, product or process input	Amount
Driver	PCB, 2-sided, 50 % SMT, 50 % THT, lead-free, including mounting processes	0.009 m ²
	Capacitors (electrolyte, film or unspecified)	18 g
	Diodes	0.6 g
	Resistors	2 g
	Transformers	48 g
	Integrated circuits	0.1 g
	Transistors	0.3 g
	Other components (active, passive or unspecified)	0.7 g
	Steel	4 g
	Plastics	130 g
	Connectors (65 % nylon 66, 27 % copper, 7 % iron, 1 % tin)	5 g
LED array	Light-emitting diodes (16 pcs)	28 g
	Silicone product; thermoforming	3.74 g
	Aluminium	23 g
Aluminium parts	Aluminium (heatsink and reflector), processing	700 g
	Coating	0.17 m ²
Other parts	Steel	17 g
	Plastics; injection moulding	26 g
	Cable	7 g
	Paper	3 g
Remote phosphor cover	YAG (yttrium aluminium garnet) coating	0.2 g
	Electricity, French mix	0.002 kWh
	Aluminium oxide	0.1 g
	Organic chemicals	0.1 g
	Plastics, injection moulding	7 g
Assembly	Electricity, French mix	0,029 kWh
Waste treatment (packaging)	Recycling of the intermediary cardboard packages	175 g

Table 1 Raw material and process inputs of the LED downlight luminaire manufacturing.

Environmental impact category	Abbreviation	Method	Unit (eq.=equivalent)
Primary energy	PE	NF P01-010	MJ
Renewable energy	RE	NF P01-010	MJ
Non-renewable energy	NRE	NF P01-010	MJ
Abiotic depletion potential	ADP	NF P01-010	kg Sb eq.
Water consumption	WaC	NF P01-010	l
Hazardous waste	HW	NF P01-010	kg
Non-hazardous waste	NHW	NF P01-010	kg
Inert waste	IW	NF P01-010	kg
Radioactive waste	RW	NF P01-010	kg
Global warming potential	GWP	NF P01-010	kg CO ₂ eq.
Acidification potential	AP	NF P01-010	kg SO ₂ eq.
Air pollution	AiP	NF P01-010	m ³
Water pollution	WaP	NF P01-010	m ³
Ozone depletion potential	ODP	NF P01-010	kg CFC-11 eq.
Photochemical ozone creation potential	POCP	NF P01-010	kg C ₂ H ₄ eq.
Eutrophication potential	EP	XP P01-020	kg PO ₄ eq.

Table 2 Environmental impact categories chosen for the LCA of LED downlight luminaire. CFC-11 refers to trichlorofluoromethane.

Figures

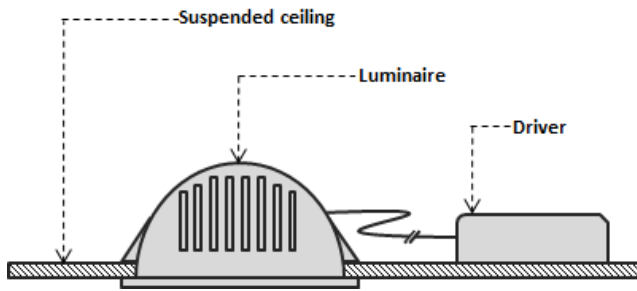


Fig. 1 Simplified diagram of the LED downlight luminaire

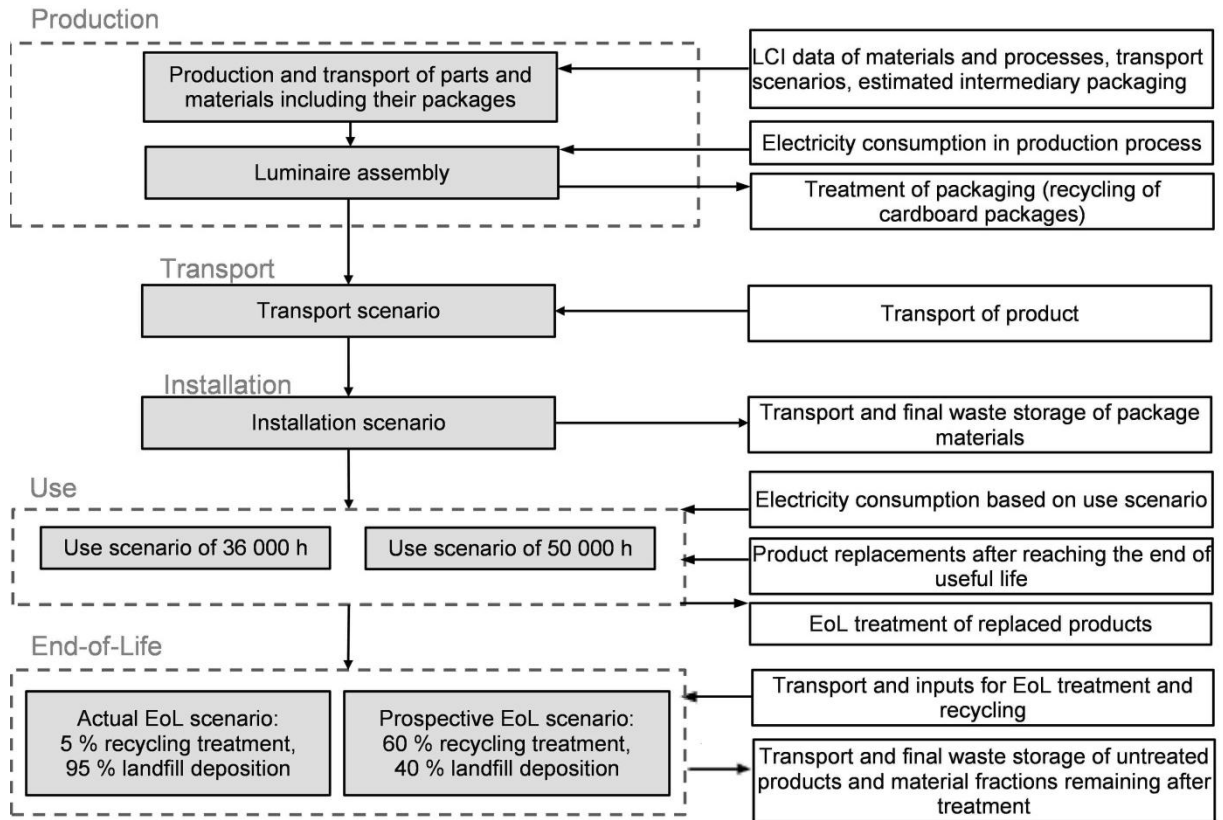


Fig. 2 Stages of the life cycle included in the LCA of the LED luminaire

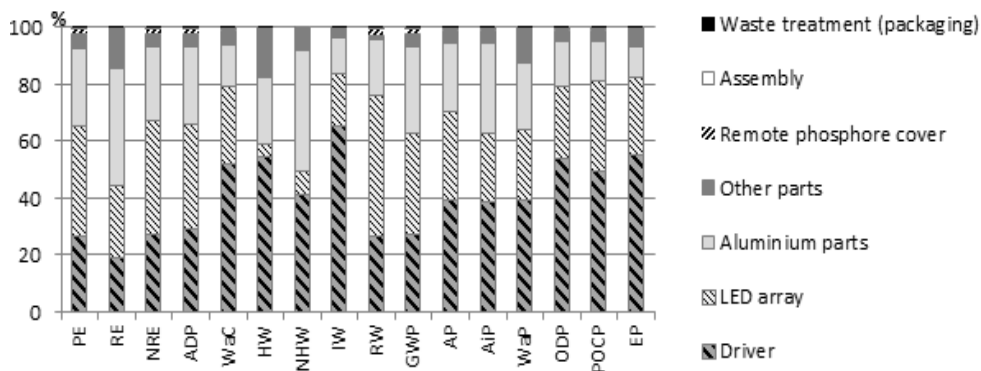


Fig. 3 Division of the environmental impacts of the manufacturing stage of the LED downlight luminaire

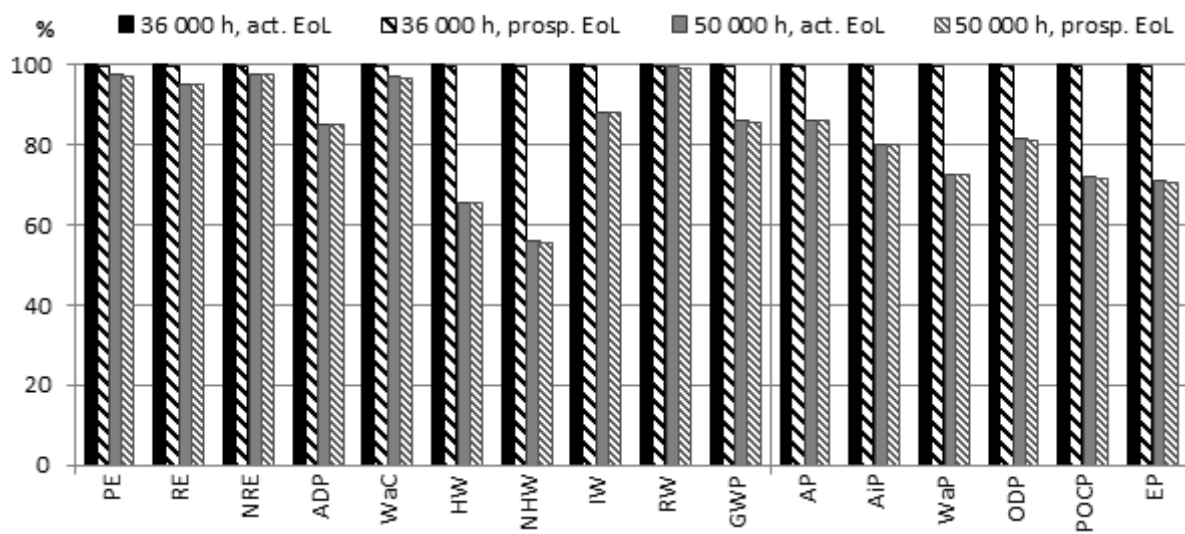


Fig. 4 Comparison of the life cycle environmental impacts of LED downlight luminaire in two scenarios of product life (36 000 h, 50 000 h) and two end-of-life scenarios (act.=actual scenario of 95 % landfill, 5 % recycling; prosp.=prospective scenario of 40 % landfill, 60 % recycling)

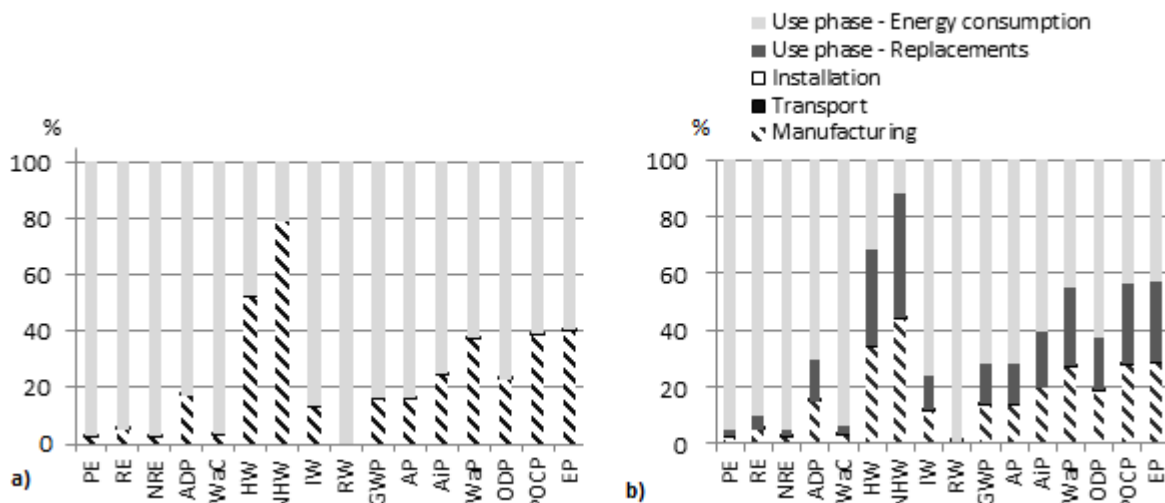


Fig. 5 Division of environmental impacts into life cycle stages when the life of the LED downlight luminaire is (a) 50 000 h and (b) 36 000 h