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Repro-light:
Re-usable and re-configurable parts for
sustainable LED-based lighting systems

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Authors:

Sebastian Knoche, TXKG

Horst Rudolph, TXKG

Johannes Gerhard Kaiser, TXKG

Maria Chabrié, TXKG

Jeanine Chrobak, BJB

Samuel Esmeijer, BJB

Manfred Neuhaus, BJB

Freddi Plikun, BJB

Burkhard Schuhmacher, BJB

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Introduction

Scope of this paper

In the light of current movements and initiatives for more sustainability, and circular economies, standardisation and regulation bodies are discussing requirements that should be imposed on luminaire designs. Of special interest is the question if (and how) components of a luminaire should be replaceable and equipped with standardised interfaces. In the ongoing discussions, some conflicting interests between different luminaire manufacturers and component suppliers can be observed, that should be taken into account to develop viable solutions.

With this deliverable, we intend to support the discussions by providing the essential Repro-light results. To this end, a concise and easily accessible summary of our Life Cycle Assessment and the quantified effects of luminaire designs with exchangeable LED modules is given. Since this is just one case study (for a specific luminaire type, and specific application), an extension to other cases is derived on the basis of qualitative arguments that were collected during the discussions while interpreting the Life Cycle Assessment results.

Additionally, the interface used in the Repro-light demonstrator with exchangeable LED modules is described. This gives an insight into one possible solution for applications that require exchangeability.

Short history and status quo of LED luminaires

The technology disruption caused by LED in the lighting industry has had a huge impact on product design, supply chain and business models. The LED offered on the first glance the industry a chance to enhance the individuality of luminaires and thus might give the manufacturers the chance to differentiate from each other. This came all at a certain cost, as companies had to gain in-depth knowledge in electronics (layout, standards and regulations) and some decided to extend also their production facilities by SMT (surface-mount technology) lines, to be independent from manufacturers of standard LED boards. At the same time, the variations in one product family increased due to more possibilities on light colour, beam angles and luminous flux classes, which lead to smaller fabrication lots. Both factors challenged the supply chains of the lighting companies especially as the innovation cycle for new LEDs is around 18 to 24 months, which is much quicker than the industry was used to from lamp technology. Bigger companies could adjust to those challenges, SMEs found their niche and how to cope with these challenges.

In Europe, the lighting industry is a very heterogeneous market which consist mainly of small and medium size enterprises (SMEs). And those are facing now not only the next technology developments such as 3D printing or smart lighting, but also changes that have an impact on their business model like scenarios of “Light as a Service” and the digital transformation. No one can foresee at the moment what lies ahead and what are the right measures to support this industry in the future.

Current standards, regulations and whitepapers

The following sections give a brief overview of the current status of standards and regulations on required exchangeability of components in luminaires.

EU regulations and resolutions

In publications of different legal status, the European Commission and European Parliament are laying down and implementing the strategy for a more sustainable Europe. This includes measures to minimise the use of resources – energy as well as raw materials – and to avoid the generation of waste.

European Parliament resolution of 4 July 2017 on a longer lifetime for products: benefits for consumers and companies (2016/2272(INI))

With this resolution [1], the European Parliament expresses its concerns about current practices that are in conflict with sustainability, and calls on the European Commission and the member states to resolve these issues. Concerns about luminaires are specifically addressed in section Z and AA of this document, stating the observations that

- "in many lamps bulbs cannot be replaced, which can lead to problems if a bulb stops working, if newer, more efficient bulbs appear on the market or if the customer's preference, for example as regards the colour of the light emitted, changes, because the whole lamp has to be replaced"
- "LED bulbs should ideally be replaceable, not irremovable, elements"

The proposed measures that shall lead to a more sustainable economy are structured into the designing of robust, durable and high-quality products; the promotion of repairability and longevity; the operation of usage-oriented economic models and the support of SMEs and employment in the EU; ensuring better information for customers; measures on planned obsolescence; strengthening the right to the legal guarantee of conformity; and the protection of consumers against software obsolescence.

Notably, "modular designs which are easy to dismantle and interchange" are explicitly encouraged. Along with that, the "fixing-in of essential components such as batteries and LEDs into products" is discouraged, unless justified for safety reasons. Concerning the repair of products, the European Parliament clearly states that independent repairers should be allowed and enabled to repair products (and not only approved firms).

Commission Regulation (EU) 2019/2020 of 1 October 2019 laying down ecodesign requirements for light sources and separate control gears

This regulation [2] is also known under the name of the Single Lighting Regulation. It enforces, as of 1 September 2021, some minimum requirements on the performance and quality of light sources. Furthermore, it requires that light sources and separate control gears in containing products are replaceable, *unless* a technical justification is given that explains why the replacement is not appropriate. The clause beginning with *unless* is very important in the context of luminaire manufacturing, since it allows to continue luminaire designs with non-replaceable light sources or control gears.

A related question is the removability of light sources. In contrast to replaceability, where the containing product must continue to work after the replacement, the simple removability just requires the light source to continue to work after removal. The removability of light sources is required by this regulation in order to enable market surveillance authorities to check if the quality and performance requirements of the light source are met. In case such a removal is not possible, the containing product itself is considered as the light source, with the consequence that the containing product must satisfy the defined quality and performance requirements and that it must be registered in the EPREL database of light sources.

In the preamble of the regulation, the European Commission states that standardisation work should address the modularisation of LED lighting products in the future, in order to promote circular economy. Article 9 of the regulation announces a review no later than 25 December 2024. One of the particular aims of the review is to assess if it is appropriate to set "additional resource efficiency requirements for products in accordance with the principles of the circular economy, especially concerning the removability and exchangeability of light sources and control gears".

EU Action Plan on Critical Raw Materials – Communication of the European Commission COM(2020) 474

The Action Plan on Critical Raw Materials [3] looks at the current and future challenges and proposes actions to reduce Europe's dependency on third countries, diversifying supply from both primary and secondary sources and improving resource efficiency and circularity while promoting responsible sourcing worldwide. The List of Critical Raw Materials has been updated to reflect the changed economic importance and supply challenges based on their industrial application. It contains 30 critical raw materials. Lithium, which is essential for a shift to e-mobility, has been added to the list for the first time.

The Action Plan on Critical Raw Materials is aimed to:

- develop resilient value chains for EU industrial ecosystems;
- reduce dependency on primary critical raw materials through circular use of re-sources, sustainable products and innovation;
- strengthen domestic sourcing of raw materials in the EU;
- diversify sourcing from third countries and remove distortions to international trade, fully respecting the EU's international obligations.

Both this recently published new EU Action Plan on Critical Raw Materials [3] and the Single Lighting Regulation [2] show that the recycling of electronic materials needs to be more focused. This will also have an impact on the design of luminaires in the medium term. Approaches for this are a better removability of light sources or an avoidance of material connections between LED boards and electrical interfaces.

EU Green Deal

The European Green Deal is an action plan provided by the European Commission to make the EU's economy sustainable, resource-efficient and competitive. To turn the European Green Deal into a legal obligation, the European Commission proposed the European Climate Law. The aim is to become climate neutral in 2050 by new initiatives along the entire life cycle of products [4].

Main aspects are to produce products which are sustainable and durable and to enable European citizens to take part in the circular economy [5]. The circular economy will grow by using resources more effectively and by processing four concentric loops: Services, Refurbish, Parts harvesting and Recycling [6].The circular economy should change the way people consume as well as the way companies produce. To avoid waste, electrical and electronic equipment should "be designed to last longer, to be easier to repair and upgrade, recycle and reuse" [5]. LED lighting for example should be designed to be repairable and to be upgradeable. It shall be possible to replace or to add components and software for better performance or for different specifications. In their standardization request M/543 the European Commission wants to define parameters and methods to assess the upgradeability and the ability to repair luminaires easily and safely. [6].

In the last quarter of 2020, the European Commission will launch the European Climate Pact as a part of the Green Deal to inform, inspire and foster cooperation between people and organisation concerning sustainable activities and new climate actions [4].

Standards

Standards by IEC TC34

The Technical Committee 34 (TC34) of the International Electrotechnical Commission (IEC) is responsible to prepare, review and maintain international standards regarding lighting equipment. For the scope of this deliverable, the safety-related standards IEC 60598-1 Ed.9.0 (Luminaires: General requirements and tests [7]) and IEC 62031 (LED modules for general lighting – Safety specifications [8]) are of special interest.

Concerning replaceable LED modules, the IEC 60598 distinguishes three levels of exchangeability for light sources: “replaceable light sources” that are designed to be replaced during normal use or during maintenance and that are connected by terminals, connectors, lamp-caps or similar; “non-replaceable light sources” that cannot be replaced without damage to the light source or luminaire, and “non-user replaceable LED modules” that can be replaced by the luminaire manufacturer, his service agent or similar qualified personnel. Furthermore, markings for luminaires with non-replaceable or non-user-replaceable light sources are required to be contained in the technical documentation.

So far, the replacement of other components than the light source is not covered by the standard, but it is planned to include this in the Edition 10 of IEC 60598-1, expected in October 2023. These situations are now becoming more common as a consequence of the use of control gears with adjustable operating parameters, and the increased demand to be able to repair or exchange control gear components should they fail or if upgrading of their performance is possible. The situations under considerations are the light source replacement, battery replacement, control gear replacement including sensors and starters, access to adjust the control gear settings. The replacements will likely include the cases of repair and upgrading. The marking requirements will be extended to these components, and the luminaire manufacturer has to declare which components are replaceable, and if the replacement is only allowed by a skilled person. Analogous to the definition of light sources, definitions of serviceable components, non-serviceable components and non-user serviceable components will be given. As an alternative to the textual markings about the replaceability of light sources and other components, pictograms will be proposed [7].

The IEC 62031 standard also defines these three levels of replaceability for LED modules. It furthermore contains safety requirements regarding the heat conducting thermal interface to the luminaire that is needed to keep the temperature below the rated maximum temperature. The standard is applicable for replaceable LED modules except for non-user replaceable LED modules [8].

Furthermore IEC 60061 – Lamp caps and holders together with gauges for the control of interchangeability and safety – contains the recommendations of the IEC with respect to lamp caps and holders in general use with the object of securing international interchangeability. Several LED related systems are already established and some more are expected to follow [9].

Standards by CEN/CENELEC JTC 10

The Joint Technical Committee 10 (JTC 10) of the two European standardisation bodies CEN and CENELEC (for electrotechnical standardisation) works on the material efficiency aspects for ecodesign of energy-related products [10]. In series of EN standards, they provide general methods for assessing and communicating product properties concerning the durability (EN 45552:2020), ability to remanufacture (EN 45553:2020), ability to repair, reuse and upgrade (EN 45554:2020), recyclability and recoverability (EN 45555:2019), proportion of reused components (EN 45556:2019), proportion of recycled material content (EN 45557:2020), use of critical raw materials (EN 45558:2019) and information relating to material efficiency (EN 45559:2019).

Designed as horizontal standards, they are applicable to all energy-related products and describe methods on a very general level. They are intended to guide the elaboration of product specific standards or to be applicable when more product specific standards are not yet available.

Standards by Zhaga

Zhaga is a global association of lighting companies that is standardising interfaces of components of LED luminaires, including LED light engines, LED modules, LED arrays, holders, electronic control gears (LED drivers), sensors, communication modules and connectivity fit systems. This helps to streamline the LED lighting supply chain, and to simplify LED luminaire design and manufacturing. Zhaga continues to develop specifications based on the inter-related themes of interoperable components, smart and connected lighting, and serviceable luminaires. It does this by creating a set of interface specifications, known as Books. A number of around 25 different Books for above mentioned product groups are already available or in preparation.

The idea for the Repro-light demonstrator was the implementation of a new interface for easy serviceable LED modules. In this case, the content of Book 21 “**Linear LED module with socket”** provided a pragmatic solution. The Book so far is under development and will be available within October 2020.

Zhaga Books can be transferred into corresponding IEC standards, e.g. Zhaga Book 14 was transferred into IEC 60061-187 – socket-holder system GR6d. A transfer to an IEC standard is also planned for Zhaga Book 21.

For more detailed information regarding existing Books and the development process visit the Zhaga website [11].

Whitepapers

ZVEI – The Replaceability of LED Light Sources

The German Electrical and Electronic Manufacturers’ Association (ZVEI) published a white paper in 2017 [12], listing the design options concerning replaceable LED light sources and recommending to keep the diversity in relation to these options. They highlight that an exchange of the LED module is often not necessary because their technical lifetime exceeds the typical usage time. The desire to exchange LED light sources rather stems from our previous experience with discharge lamps or incandescent lamps. A distinction between the following design options is made, all being valid solutions (depending on the application): Replaceable by an end user (without tools), replaceable by a professional (on site), replaceable by the manufacturer (at factory) or not replaceable at all. Examples are given, in which product designs with non-replaceable LED modules make sense, e.g. luminaires with a high ingress protection class to be used in harsh conditions like animal husbandry or certain industrial applications.

Since this paper is already three years old, the decision was made to update the existing white paper with respect to the new Ecodesign requirements. The new version is expected to be available end of year 2020. The scope is the replaceability, repairability, modularity and circular economy of luminaires and its components.

LightingEurope – Serviceable Luminaires in a Circular Economy

LightingEurope, the European association of the lighting industry companies, has published a white paper in 2017 [6], where a discussion of the circular economy is given and some examples for the applications and services concerning luminaires with exchangeable components are described. The examples of applications that require exchangeability include repair and maintenance in order to elongate the product lifetime, the upgrade to the latest state of the technology and a changed characteristic (like colour temperature) requested by the user.

In regard to EU policies, however, the clear statement that it is too early to introduce regulatory requirements at this stage. Instead, the lighting industry should work on a voluntary basis to explore all options regarding luminaire designs and different levels of exchangeability. However, it is proposed to elaborate a standardised information scheme regarding the serviceability of luminaires. A first exemplary draft of such an information scheme is given, and the note that such a scheme could be subject of future EU legislation and could be used in public procurement if serviceable luminaires shall be promoted.

Implications from an in-depth Life Cycle Analysis

Case study – quantified effects of exchangeable light sources

Brief introduction to environmental Life Cycle Assessment

An environmental Life Cycle Assessment (LCA) quantifies the environmental burdens of a product over its entire life, from production over use phase up to the disposal. In Repro-light, we conducted a cradle-to-grave LCA for a lighting system of continuous line LED luminaires [13] [14]. Such continuous line lighting systems are often installed in industry halls, but also in shop/retail applications, offices, educational facilities, and more.

The research, led by the LCA team of the Catalonia Energy Research Institute (IREC), pointed out the major contributions to the environmental burdens of the benchmark luminaire. The benchmark luminaire is a LED based luminaire, but on the state of technology of about three years ago before the Repro-light project started. One of the outcomes is that we need to distinguish the use of two independent resources: energy and material. The energy consumption is quantified as the Primary Energy Demand (PED) in units of Megajoule (MJ), whereas the raw material use is quantified by a metric called Abiotic Depletion Potential of the Elements (ADPe) measured in units of kilogram Antimony equivalent (kg Sb-eq.).

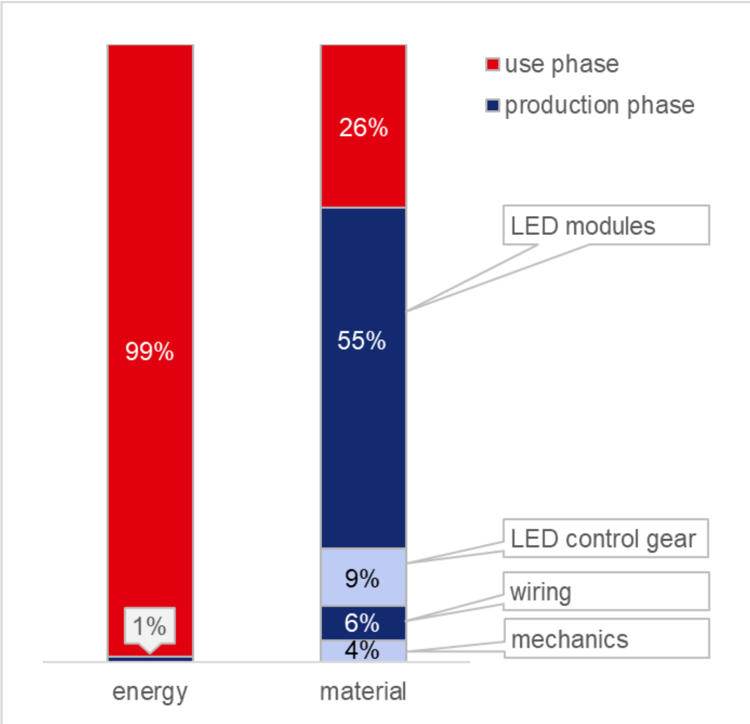


Figure 1: Summary of the environmental burdens of the benchmark luminaire.

Figure 1 shows the results of the LCA. Concerning energy consumption, the use phase (in this model 70.000 hours, corresponding to the luminaire lifetime L80) clearly dominates and contributes 99%. The material use stems largely from the production phase (a total of 74%), plus some contributions in the use phase that are needed for the energy production (power plants, infrastructure, etc.). The production phase is split into the contributions of the individual components, and we can see that the electronics components (LED modules and control gear) have the largest impact due to their use of precious materials like gold, copper, lead, and more. We found that the contribution of the optics is so small that it can be neglected (< 0.1%) in this impact metric. Notably, the largest and heaviest parts of the luminaire, its mechanical structure and housing, have a relatively small contribution. This is important to be aware of, since this might mislead our intuition about the expected benefits of exchangeable components to keep others in continued use.

Further details are published in references [13] and [14], including a comparison to a next generation luminaire with improved design for material efficiency. For the scope of this deliverable, the numbers presented here are sufficient to reason about the sense of designing luminaires with exchangeable components.

Design choices: material efficiency and modularity with defined interfaces

The eco-design guidelines [14] published by the Repro-light consortium contains several checklists with concrete ideas how the sustainability of LED luminaires can be improved by the product design. Here we want to focus on the question if exchangeable components improve the sustainability or not, because this is an ongoing discussion in standardisation and regulation.

There are two diverging design paradigms, that are both perfectly plausible to enhance the sustainability of a product, but are not reconcilable:

- *Maintenance-free, material optimised design*
  Create long-living luminaires where all components have a lifetime corresponding to the typical usage time, and which are optimised for little material usage by integrating several functions in a component, e.g. using sheet metal flaps of the housing to clamp the LED module instead of using additional clips or screws. The components need not (and cannot) be serviced during the luminaire life.
- *Design for modularity and interchangeability*
  Make the LED module easily exchangeable, like replaceable lamps in earlier times, accepting additional components/material for the sake of easy exchangeability. The main focus are products which offer the re-use of materials or components. As a benefit, those luminaires offer customers the repairability of the key components (LEDC & LEDM). This would lead to the replacement of currently used components such as SMD connectors in favour of new components which offer an interface for an easy modular system architecture.

Design for exchangeability does not come for free, it is related to a more elaborate design in which additional components, like plug/socket connectors or fastening elements are needed. In the following two model calculations, we compare these two approaches in a quantitative way based on the LCA results presented above. A more detailed description of these model calculations can be found in reference [13].

Exchangeable LED modules for repair

One of the benefits of exchangeable LED modules is that a luminaire can be repaired in case an LED fails, and does not need to be replaced as a whole. We thus waste less material – this material saving must be balanced against the excess material consumption needed to ensure exchangeability. If the approach of exchangeability pays off crucially depends on the failure rate of the LEDs.

Based on a Weibull analysis of after-sales data in this luminaire category, we can expect that just around 1% of the LED luminaires will fail before their rated lifetime ends. Literature suggests that the majority of failures occurs due to the LED control gear (more than ¾ of the failures); the LED module itself is not very prone to failure [15]. For the scenario calculation, we assume a lighting system of 369 luminaires, and expect that 4 will fail before the end of their rated lifetime, among these 3 due to the control gear and 1 due to the LED module.

In design (i), only the control gear is exchangeable (as it is common practice today in most of the luminaires), but the LED module is not. Thus, the one luminaire that has a failing LED in our scenario must be replaced as a whole; the three luminaires that have a failing control gear can be repaired by replacing the control gear.

Design (ii), in contrast, is equipped with an exchangeable LED module (and, of course, an exchangeable control gear). Thus, the one luminaire with a failing LED can be repaired by replacing the LED module, keeping the rest of the luminaire in continued use, thus saving material for the spare parts. However, there is additional material consumption to ensure the exchangeability, in our proposed design this is a plug-and-play connector. The LCA shows that the contribution of the additional connectors is just 0.4% to the overall ADPe impact of the luminaire. But this extra contribution for the connectors applies to *all* of the 369 luminaires in our scenario, to achieve a benefit in only *one* case.

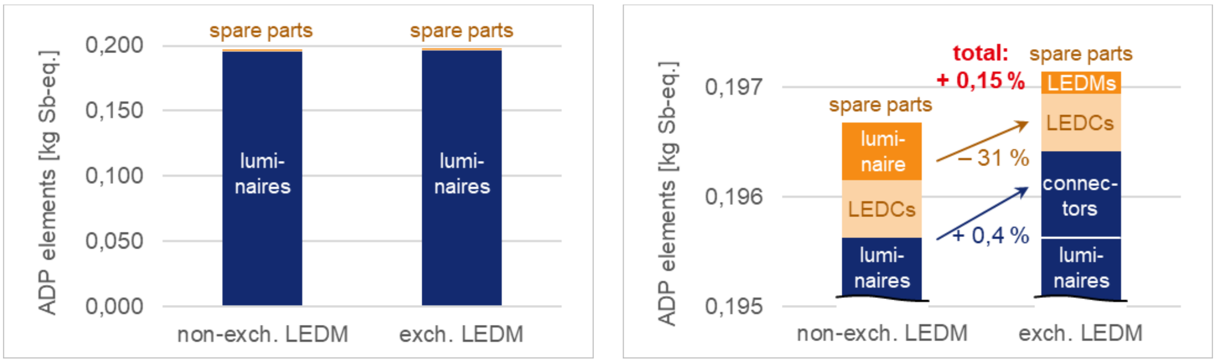


Figure 2: Comparison of the material consumption of a (i) design with non-exchangeable LED module and (ii) design with exchangeable LED module. Left Diagram: Total material consumption, measured by ADP elements impact metric. Right Diagram: Close-up of the top of the bar chart to make the differences visible.

The quantitative comparison of designs (i) and (ii) shows that in total, the variant with exchangeable LED module has a higher material consumption than the variant with non-exchangeable LED module, see Figure 2 and reference [13] for the full report. In the case of such small fraction of LED modules that are expected to fail, the exchangeability of LED modules does not pay off.

Exchangeable LED modules for maintenance

A different use-case of exchangeable LED modules that is often discussed, is the option to replace degraded LED modules by new ones in order to restore the energy efficiency of the luminaire. This idea is based on the fact that LEDs degrade slowly over time, that is, their luminous flux and luminous efficacy decrease [16]. One consequence is a maintenance factor that needs to be included in the light planning, ensuring sufficient illuminances at the end of the luminaire lifetime.

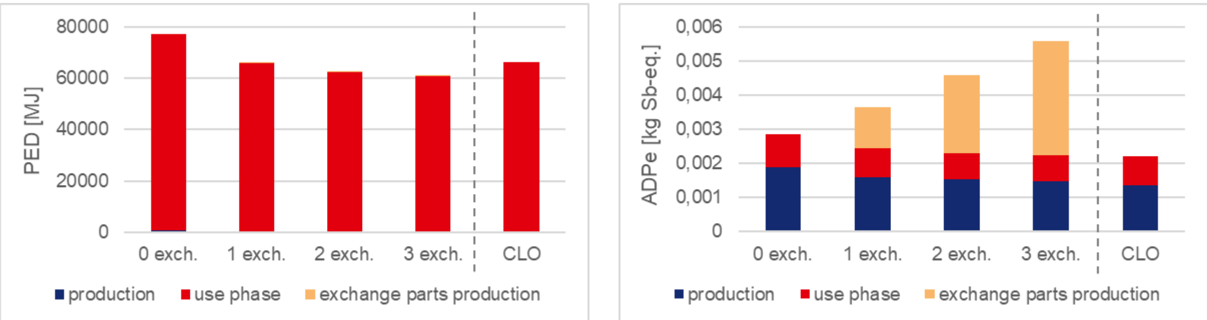


Figure 3: Environmental impacts (left diagram: energy consumption; right diagram: material use) in scenarios where LED modules are exchanged between 0 and 3 times in order to restore the efficacy of the luminaire. The fifth scenario shown is the constant light output (CLO) technology.

An apparent solution to both points, efficacy decrease and maintenance factor, is the regular replacement of LED modules in shorter time intervals, so that they do not degrade so much. The obvious drawback of this approach is that it generates more LED module waste than necessary, because it leads to LED modules being disposed off that are still working (albeit at lower efficacy).

We performed a model calculation over 100.000 hours of use, corresponding to the L_{70} lifetime [16] [17] of the benchmark luminaire. The scenarios consider up to 3 exchanges of the LED modules during the usage time of 100.000 hours. The quantified energy savings and material consumptions are shown in Figure 3.

As qualitatively expected, the energy consumption can be reduced, at the cost of increased material use and waste generation. Since material and energy are two fundamentally different resources, it is impossible to balance them unless their value can be quantified on a common scale. Consequently, it is not possible to decide which scenario is the “most sustainable” one.

However, there is one additional solution considered, termed constant light output technology (CLO). In this approach, the luminous flux degradation is compensated by adjusting the forward current through the LEDs. There is no need to replace the LED module in this technology, it is purely software-driven. This does not stop the decrease in luminous efficacy of the luminaire, but it solves the impact of the maintenance factor and the over-illumination at the beginning of the operating time. This scenario ends up with the smallest material usage of all scenarios considered, and a medium rank concerning the energy consumption, see Figure 3.

Lessons learnt and principles for qualitative reasoning

The in-depth Life Cycle Assessment and the model calculations show, that ***exchangeability of components does not necessarily lead to more sustainability***. Exchangeability does not come for free, it requires a more sophisticated design than a material-optimised, maintenance-free luminaire. If the benefits of replaceable LED modules outweigh the extra materials needed to enable the replacement must be evaluated in each case.

Furthermore, the Life Cycle Assessment shows that ***the physical weight of components [in kg] and their ecological importance [ADPe in kg Sb-eq.] are disproportionate***. The smallest elements (e.g. the gold bond wire in LEDs) can have the largest environmental effect. This misleads intuition.

Replaceable components are often expected to elongate the usage time of products. However, there are many cases in which the technical lifetime of products is not the limiting point for using the product. This is also true for some lighting applications, as LightingEurope showed on the basis of typical refurbishment cycles of building interiors [17]. If the technical lifetime of the product is longer than its typical usage time, we must give a more thorough consideration to the question ***why are luminaires disposed, actually?*** Finding the modes that are responsible that luminaires are disposed before the end of their technical lifetime then lead to design improvements to circumvent them.

Studies suggest that ***electronics waste is poorly recycled*** in industrial practice [18]. Today, primarily the mass metals (housing etc.) can be recycled, but not the ecologically relevant materials. Although it is good and legitimate to call for better recycling and recovery technologies, the lighting industry has to accept the current limitations of electronics recycling when improving luminaire designs. Customers often expect that LED modules (and other electronics) can be given to the recycling process, evoking the impression that it is not doing much harm to the environment to dispose electronics components because materials can be recovered. It is important to inform that there is no actual circularity for electronics components today, and that we should therefore focus on using the products as long as possible.

Nevertheless, there is also an emotional aspect. If the customer has the option to replace an LED module or other components, it is ***perceived as more sustainable***, even if a quantitative LCA shows different results. This might increase interest in luminaire designs with exchangeable components in the market. It might also be (mis)used to make customers believe that some products are more sustainable, an action called *green washing*.

A last insight that was obtained in discussions of the LCA results are the following ***factors that were identified to influence the meaningfulness of exchangeable components***: i) luminaire type, ii) application, iii) manufacturer (large player vs. small or medium enterprise), iv) business model / usage concept of the luminaire. The scenarios discussed in the following section will relate to these factors and show their influence.

Extension to other applications and luminaire types

Different applications and luminaire types require different approaches concerning the replaceability of components. The principles summarised above enable us to lead qualitative discussions and find the critical points how the sustainability of lighting products can be increased. We propose the following framework to classify the modularity of a luminaire:

- Component exchange scheduled (yes/no): If yes, a component exchange within the luminaire lifetime is expected, e.g. for upgrading to newer and more efficient LEDs, or because a component has shorter lifetime than the luminaire. If no, all components have a lifetime corresponding to the typical usage time; an exchange would only be required in the unexpected case of a failure (repair).
- Preferred modularity: A code consisting of (i) numbers indicating the components that can be exchanged, (ii) a letter to indicate if the components are built-in or external, respectively, and (iii) a letter to indicate if a toolless exchange is possible or if a tool or special tool is required.
  i. 0 = no component exchangeable;
     1 = electronic control gear, LED module and optics are replaceable as one unit;
     2 = LED module and optics are replaceable as one unit;
     3 = the LED module (light source) is replaceable;
     4 = the electronic control gear is replaceable
  ii. B = Built-in component (luminaire needs to be opened for replacement);
     E = external component
  iii. L = toolless;
     T = tool required;
     S = special tool required.

To give an example: The conventional luminaires with fluorescent lamps (T5) do require a component exchange (the T5 lamp has a shorter lifetime than the usage time of the luminaire), and their usual modularity was 3-B-L: The light source was built in the luminaire, but could be replaced without tools.

The two examples of our case study presented above can be coded as follows. In the "non-exchangeable" case, a replacement of the light source is not expected and not possible. The complete gear tray can be exchanged (without tools): code 1-B-L. The other case, using plug connecters to enable exchangeability of the LED module, would be coded as 3-B-L. Our quantitative analysis showed that the first approach (1-B-L) should be preferred in the discussed industry, office and retail application.

Scenario: Light as a Service

At the moment, the typical duration of a Light as a Service contract is around 5 years. This means that the usage time in the product's first life (20.000 hrs in an industry 2-shift application) is significantly smaller than its lifetime (50.000 – 100.000 hrs). A second life is therefore reasonable and requires reconfiguration of luminaires, because the possible variants are too manifold to find a matching project for the luminaires in their current configuration.

This business model *requires exchangeability of all components*, code 3/4-B-T or 3/4-B-L, unless it is technically not possible.

Nota bene: This is circularity, but not necessarily more sustainable! It only increases the sustainability if the cumulative usage time is longer than the usage time in the standard business of selling lighting systems and operating them up to their respective technical lifetime.

As the LCA was so far only done for a continuous line luminaire, it should be taken into consideration to do similar assessments for other type of luminaires, like downlights or panel luminaires.

The economic viability of this model depends on how customers will accept luminaires that are offered in their second life after a first usage. One important point will be how quick and significant the technology change will be during those first 5 years. The less this becomes, the more customers might be willing to accept products in their second life. We point out that there is a risk that a Light as a Service business model that is really more sustainable than the traditional business models might not be economically viable.

Scenario: Office lighting with standard ceiling grid

Standard office ceilings consist of panels that are about 60x60 cm large. Panel luminaires are designed to be compatible with the ceiling grid, replacing some of the ceiling panels with areal luminaires. They are designed in a very material and cost efficient way, consisting of a sheet metal housing, some dozens of LEDs and a plastic cover. Comparing the design to our benchmark luminaire in the Life Cycle Assessment, we can expect that the major contribution concerning material consumption comes from the LEDs, with only small quantities added by the cover and housing. Their technical lifetime corresponds to their typical usage time. The LED modules are quite reliable, the control gears are more prone to failure.

Figure 4: Office with standard ceiling grid and panel luminaires. The panels, with external control gears, show little to no design differentiation between manufacturers and can be replaced 1:1 in case of a failure.

We can assume that the typical reason for a luminaire disposal is either because the office is being refurbished, or because a control gear has failed.

This suggests that control gears should be kept external and exchangeable (code 3-E-L), but that LED modules are okay to be non-exchangeable. If they fail, they can be replaced in a unit wit the optics (and the sheet metal housing where everything is attached).

Scenario: Office with "designer luminaires"

An interesting effect on the question "what determines the end of life" takes place in a designer office. Consider an ensemble of high-quality designer luminaires, for example eight TRILUX Lateralo luminaires in a presentable meeting room. What happens if *one* luminaire fails after eight years, cannot be repaired because spare parts of that state of technology are not available, and new luminaires of the same type are not available anymore? The consequence will be that *all eight* luminaires will be replaced by new designer luminaires.

To improve the sustainability, the luminaires should be designed to be repairable, at least by the luminaire manufacturer himself. The components need not be replaceable for maintenance (foreseen replacement), but for repair reasons. Given the uncertainty about the actual failure rates of control gears or LED modules for the designer luminaire, a safe way is to make all components exchangeable, code 34-B-T. However, due to aesthetic design requirements and economic considerations, especially in designer luminaires there may be technical reasons that justify that an LED module is not replaceable: Using standard components and interfaces limits the design space for the luminaire; and custom designed interfaces may be too expensive, being used only in that designer luminaire. An experimental approach to circumvent this using 3D-printing is shown below, see section *Approach for downlights with COB LEDs* below.

Figure 5: Office lighting with high-quality luminaires with sophisticated design. In case one luminaire fails and cannot be replaced or repaired (e.g. because components with that state of technology are not available any more), all luminaires will be replaced.

Scenario: Shop lighting with downlights

In shop lighting, downlights with COB (chip on board) LEDs are frequently used. This type of LEDs is less efficient than the mid-power LEDs used in the Repro-light luminaires, because the LED chips shadow each other, and their thermal management is less efficient than for mid-power LEDs. Some progresses in the LED technology are still expected, but they slow down. The market of COB LEDs is quasi-standardised: Many COB manufacturers use similar or identical light emitting surfaces. This simplifies the sourcing of spare parts and allows to design luminaires with standard, exchangeable LED modules (code 3-B-T). The control gears should be kept externally since they are prone to failure.

Due to the technology progress in the COB LEDs, we can expect luminaire upgrades to be released quite often. In order to keep them compatible with previous versions and to allow extending lighting systems, features like the diameter (of the ceiling cut-out) or the visual appearance (the "face") of the luminaire should stay constant.

Summary of observed effects and influencing factors

The above scenarios demonstrate that the preferred modularity of luminaires cannot be answered once and for all, but depends on several factors.

We observed that a distinction between designer luminaires and mass market products could be reasonable. For material-optimised mass market products, like standard office panel luminaires, the replacement of LEDs, optics and housing as one unit can make sense, and is possible since the luminaire appearance is quasi-standardised. The control gears are preferably kept separate and easily exchangeable. For designer luminaires, repairability is a much more critical point, because the failure of just one luminaire might cause the replacement of a whole ensemble of luminaires.

Another aspect is the handling of future technology innovations. Are the LEDs used in a luminaire close to maturity, or are upgrades, especially concerning their energy efficiency, expected? Only if sufficient increases in energy efficiency are expected, models with scheduled replacements of the light source provide a sustainability benefit – otherwise it is a waste of material resources.

Furthermore, the business model has an effect on the product design. With changing business scenarios, the needs of the lighting industry might change towards a new openness for discussions on standardized interfaces. In the above scenario, we saw that a Light as a Service business model with short contract periods require the re-use of luminaires to generate a sustainable effect with this circular model. Since luminaires are needed in a large number of variants (regarding luminous flux, luminous intensity distribution, light colour and other features), it is unlikely that luminaires dismounted in one building can be used directly an unaltered in a matching project. This requires the reconfigurability of luminaires, for example by exchangeable optics, LED modules, and reprogrammable drivers.

We expect even further factors that determine the preferred modularity, that could not be discussed in detail here. Examples are the needs of companies with different sizes (large ones versus SMEs) and the question if the standardisation of components leaves enough degrees of freedom to generate unique luminaire designs.

Interface used in the Repro-light Demonstrator

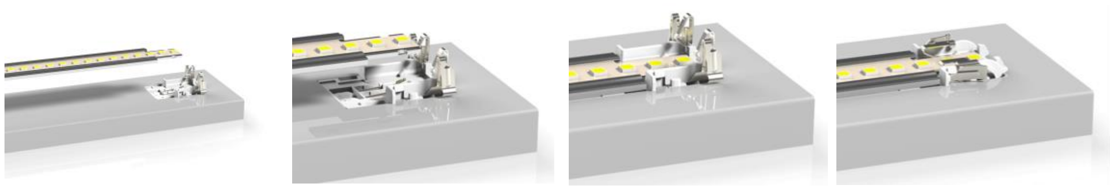
One of the Repro-light luminaire demonstrators was designed for easy exchangeability of the LED module using the Quick-Connect system of BJB. It provides the opportunity to efficiently install and remove LED modules without great cost or time investment. It is based on the (currently not yet released) layout as described in the Zhaga Book 21, using a standardized interface design to connect and secure the electrical connection.

Working principle

Assembly

1) First of all the connector is clipped into the luminaire housing. Placement is done by inserting the back of the connector diagonally, and pressing down on the front to engage the snap-fits.

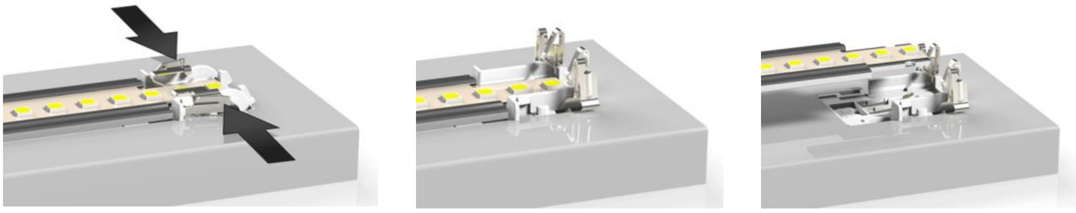
2) After the connector is in place, the LED module can be positioned on top. When correctly positioned, the metal spring can be rotated down on top of the module, and pressed down to snap into place. The spring has two functions: providing a mechanical fixation for the LED module, and ensuring sufficient downforce on the contacts to create a good electrical path. Enough force is required for the connector to reliably function over longer lifetimes.



3) Aside from the connector, metal springs holding the rest of the LED module in position were developed based on an existing Zhaga Book 21 compliant LED module. Although there are alternative ways to fix an LED module, the springs are made with the same goal in mind to be able to quickly replace the modules. To install the LED module, it only needs to be pressed down between the clips, and the snap-function will engage to hold it in position.
4) The clips themselves can be placed in a simple rectangular opening in the luminaire body, and pressed down to engage the snap-fit. This is very easily done with a long narrow tool, such as a flathead screwdriver.

Disassembly

1) With replaceability as a priority in the design, removing an LED module is a simple and fast process. The connector has two ‘wings’, which can be pressed to release the snap-fit. At this point the metal spring can be rotated up, and the LED module can be removed.



2) The metal springs that hold the rest of the LED module are released by spreading them outward, after which the module can easily be removed.

In the Repro-light project no new proposal for standardised electromechanical interfaces has been developed. On the one hand, the Repro-light consortium was not broad enough with a sufficient number of industrial partners to prepare a later market acceptance. On the other hand, the development of the new Zhaga Book 21 interface outside of Repro-light had arisen during the project start-up phase.

The requirements of both applications are very similar. The development of two competing systems should be avoided during a standardisation process in order to achieve a broader dissemination (not only for Repro-light luminaire), better market acceptance and much more cost-effectiveness.

In order to use synergies, the Zhaga Book 21 connector was designed into the Repro-light exchangeability demonstrator, see Figure 6.

Figure 6: Zhaga Book 21 connector designed into the Repro-light exchangeability demonstrator

Discussion

Benefits of standardised interfaces like the Zhaga Book 21 connector

The fixed electrical and mechanical interface makes it easier for luminaire manufacturers to develop solutions that work well with systems from different suppliers. Furthermore does it give the possibility to upgrade or reconfigure the luminaire easily for example for re-use or to improve energy efficiency.

It supports the assembly and disassembly of light sources in a time and cost efficient way without complications. This also allows Late-Stage Finishing, that is, the ability to finish luminaires at the latest possible time. There are many variants that can be chosen for luminaires, including colour temperature, luminous flux and luminous intensity distribution. It is of benefit for manufacturers to place LED modules as the final step very quickly, avoiding the need for large stock-keeping of finished goods and it could reduce the delivery time.

Limitations

Current limitations include the availability of only rear-side connections. With traditional LED PCBs, the material cost is considerably increased because of the required contact pads on the back of the module. An existing, on the market available Zhaga Book 21 compliant LED module shows that this problem can be circumvented.

Another limitation of this particular design is its use for only SELV solutions (electric potential below 60 V). Non-SELV solutions are also expected to be developed as the standard becomes more widely accepted.

Approach for downlights with COB LEDs

Other applications require point-like luminaires (downlights), and not only linear luminaires. In such luminaires, connectors are mainly used for electromechanical connection of COB (Chip on Board) LEDs. On the one hand, COBs and their interfaces are quasi-standardised on the market. A design study on 3D printing integration carried out in Repro-light has shown that customised luminaires are also possible despite the use of standard components.

Conclusions

In this paper, we discussed which components of a luminaire should be replaceable and preferably equipped with standardised interfaces. We started with a review of standards, regulations, and white papers on this topic. After that, we presented an unbiased analysis of the advantages and disadvantages of exchangeable, standardised modules in a luminaire from the perspective of a Life Cycle Assessment. We presented the quantified effects of exchangeable light sources obtained in a case study. From that specific case study, we formulated lessons learnt and concluded principles for a qualitative reasoning. This abstraction allowed us to extend the discussion to other applications and luminaire types, but only on a qualitative and not a quantitative level.

The question, which components of a luminaire should be replaceable, cannot be answered once and for all at this stage. Depending on the luminaire type, application, manufacturer and even the business model, different requirements on the replaceability are obtained in order to improve the sustainability of luminaires. In contrast to the intuitive understanding and common assumption, the replaceability of light sources is not always the most sustainable solution, as our quantitative case study and qualitative discussion has shown.

We have seen that there are lighting applications, in which the technical lifetime of the luminaire is not the limiting factor, since it is already longer than the average usage time. In such cases, an option to replace parts in order to elongate the luminaire lifetime will have no effect on the sustainability, as it will remain unused.

Different conclusions can be obtained in other scenarios, for example that of a Light as a Service business model. With usual contract periods being much shorter than the technical lifetime of the luminaires, the service providers will face the challenge to monetise the residual value of the luminaires after their first, comparatively short, life. One approach is the re-use of the luminaires or components, where a reconfiguration might be required to match the luminaire characteristics with the new application, thus requiring a modular system with replaceable components.

Recent European regulations on the ecodesign of lighting products are forcing the industry towards more modularity and replaceability of light sources and control gears. The Commission Regulation (EU) 2019/2020 will apply in all EU member states as of September 1st, 2021. More strict requirements are expected for the future. According to an estimation by the ZVEI, the interchangeability of components and the reusability of materials and products will increasingly become the focus of EU regulations. Especially for future developments it is already recommended nowadays to consider the implementation of a modular luminaire design [19].

However, it I still to be clarified who has the product responsibility for luminaires with replaced components. Given that light sources and control gears are not as strictly standardised as lamps in earlier times, performing a replacement requires technical expertise. The safe way is to leave such modifications of luminaires to experts, either the luminaire manufacturer himself or other skilled persons. Replaceability for the unskilled end-user is of the luminaire is not feasible with luminaire designs comparable to current LED luminaires.

On the first glance, a modular luminaire design might look more complicated than the system designs of today. Nevertheless with detailed and focused new developments in combination with the evolution of new products also future luminaire designs will have a new simplicity with benefits of economic advantages.

Finally, we should note that all proposals concerning repairability, replaceability, and standardised interfaces need to be economically viable. If the repair of luminaires or re-use of component turns out to be significantly more expensive than the production of new luminaires or components, the mass market will not accepted this approach, and the option to repair or re-use will remain an unused option. This risk is actually quite high, since the highly automated, highly efficient industrial production leads to low production costs, whereas repair and re-use is not automatable.

In the end there will not be one general solution, but various concepts and adaptions driven by the above mentioned points as well as the future technology development and innovation. Nevertheless, the lighting industry will have to find a way between material optimised product design and modular system architecture.

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