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The role of life cycle assessment in the implementation of circular economy in sustainable future

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Abstract
Life Cycle Assessment (LCA) is an important tool of Circular Economy (CE), which performs the analysis in a closed loop ("cradle-to-cradle") of any product, process or technology. LCA assesses the environmental threats (climate change, ozone layer depletion, eutrophication, biodiversity loss, etc.), searches for solutions to minimize environmental burdens and together with CE contributes to reducing greenhouse gas emission, counteracts global climate crisis. The CE is a strategy for creating value for the economy, society and business while minimizing resource use and environmental impacts through reducing, re-using and recycling. In contrast, life cycle assessment is a robust and science-based tool to measure the environmental impacts of products, services and business models. Combining both the robustness of the LCA methodology and the principles of circular economy one will get a holistic approach for innovation. After a presentation of the LCA framework and methods used, examples of case studies of comparative LCA analysis for replacement materials to reduce environmental load and their challenges as assessment methods for CE strategies are presented. It was concluded that there is a need for improvement of existing solutions, developing the intersection between the CE and LCA. Suggestions for developing a sustainable future were also made.

Keywords
Sustainability Development Goals, Life Cycle Assessment (LCA), Circular Economy (CE), indicators of CE, implementations of LCA

1. INTRODUCTION

The most commonly quoted definition of sustainability: "Sustainable development is development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" comes from a report by Gro Harlem Brundtland, Prime Minister of Norway (United Nations, 1987). Sustainability was explained in depth in this 300-page document through the discussion of climate change, economic development and global goals that should be implemented. Sustainability is based on three fundamental pillars: environmental, economic and social. The foundations of environmental sustainability are: safeguarding water, saving energy, reducing waste, using recyclable packaging, limiting or eliminating the use of plastics, using sustainable transport, reusing paper and protecting flora and fauna. Economic sustainability refers to the organization ability to manage its resources and responsibly generate profits in the long term, while social sustainability in particular has the goal of strengthening the cohesion and stability of specific social groups.

To gain an understanding of sustainability and its implication it is essential to mention 17 Sustainability Development Goals (SDGs) and the 2030 Agenda (United Nations, 2023). The UN report highlights the need to make major progress if we want to achieve the Sustainable Development Goals by 2030. However, according to the United Nation annual report analysing how each goals is progressing, UN Secretary-General Antonio Guterres in March 2022 warned that humanity is moving backwards in relation to the majority of the SDGs. As outlined in the report by The Intergovernmental Panel on Climate Change (IPCC), even if greenhouse gases are radically reduced right now, average global warming will most likely exceed 1.5 °C in the near future (IPCC, 2022). Such a temperature increase can have disastrous consequences, like the melting of glaciers, the disappearance of animal and plant species, forest fires and droughts, among others.

In 2021, the UN's International Energy Agency (IEA) estimated that a global energy transition of fossil fuels would increase demand for key minerals such as lithium, graphite, nickel, and rare earth metals by 4200%, 2500%, 1900%, and 700%, respectively, by 2040 (International Energy Agency, 2021). However, there is no capacity to reach such a demand. Critical raw materials are the backbone of modern economies and are key components of future development. Their use has serious environmental and social consequences, from extraction to disposal. Therefore, resource conservation aims to establish a circular economy that keeps products and raw materials in economically valuable loops, moving from waste to resource.

The circular economy (CE) stands for an economy, which maintains the value of materials for as long as possible while minimizing waste generation and emissions by closing material loops along life cycles of products and services. The CE concept's life-cycle thinking helps to implement the waste hierarchy laid down by focusing on waste prevention. Implementing the CE concept systemically requires a shift from linear to circular systems, thus calling for system transformation in production, consumption and governance systems as well as in society. It is necessary to develop promising interventions in order to facilitate this transformation. While circular economy strategies can be implemented in various sectors such as industry, waste, energy and transportation life cycle assessment is required to optimize new systems (Hauschild et al., 2018).

A quantitative analytical method to quantify environmental impacts of a product, a service or a production process is needed. The only necessary evaluation method is provided by Life Cycle Engineering (LCE), which is a sustainability-oriented methodology, which takes into account the complex technical, environmental and economic impacts of life cycle decisions. The definition of LCE is "an engineering activity that involves the application of technological and scientific principles to the manufacture of products in order to protect the environment, conserve resources, promote economic progress, keeping in mind social concerns and the need for sustainability, while optimizing the life cycle of the product and minimizing pollution and waste." (Hauschild et al., 2018). As can be seen from the quoted definition, however, LCE includes, in addition, social aspects that are difficult for engineers to quantify. Therefore, the present article is limited only to the basic LCE tool of life cycle assessment (LCA).

Life cycle assessment (LCA) is a standardized tool to evaluate the environmental impacts associated with all the stages of a product's life, which is from raw material extraction through material processing, manufacture, distribution, use and disposal. Nowadays, LCA analysis is particularly important for emerging technologies that have not been tested in real operating conditions. The results of the analysis, which allow to draw conclusions at the design stage, are also of great importance. Consequently, LCA analysis is becoming an integral part of projects developing new technologies with market implementation potential.

After a brief presentation of the LCA methodology (Goals and Scope, Inventory Analysis, Impact Assessment, Interpretation) and the methods used (e.g. IPCC, 2022, ReCiPe and others), as well as the software programs that are implemented, examples of specific LCA applications and their challenges as assessment methods for CE strategies are presented.

2. LCA METHODOLOGY

Life Cycle Assessment is one of the prominent tools for estimating environmental sustainability (Finnveden and Moberg, 2005). The methodology of LCA is internationally standardized; ISO 14040:2006 and ISO 14044:2006 standards normalize principles and framework, as well requirements and guidelines of analysis. A dynamic development of the LCA methodology reported over the last 25 years has resulted in the expansion of new computational techniques and extensive databases allow to obtain the information about environmental burden generated by the product or process during the entire life cycle.

ISO has defined LCA as a technique for assessing the environmental aspects and potential impacts associated with a product system by:

- Compiling an inventory of relevant energy and material inputs and environmental releases of a product system.
- Evaluating the potential environmental impacts associated with identified inputs and outputs.
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

A complete LCA consistent with ISO 14040:2006 series standards is composed of four interrelated phases as presented in Figure 1.

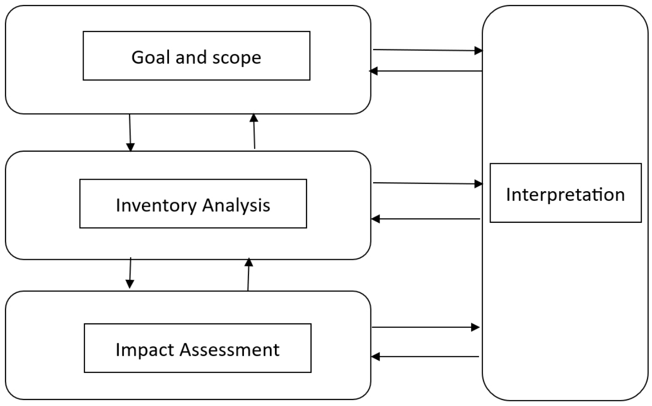

Figure 1. Life cycle assessment according to ISO 14044:2006.

1. Goal Definition and Scoping is to define and describe the product, process or activity; establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment. All elements described here such as purpose, scope and main hypothesis considered are the key of the study. The key issue is the definition of the functional unit (FU). The FU is a measure of the performance of the product system. The purpose of the FU is to provide reference to which all inputs and outputs are related. Another aspect is to set the boundaries of the system. Decision must be made on which unit processes or activities will be included in the studies (Figure 2).
    - Cradle-to-grave is the full life cycle assessment starting from extraction of row materials ("cradle") to the use and disposal phase-landfill, incineration ("grave").

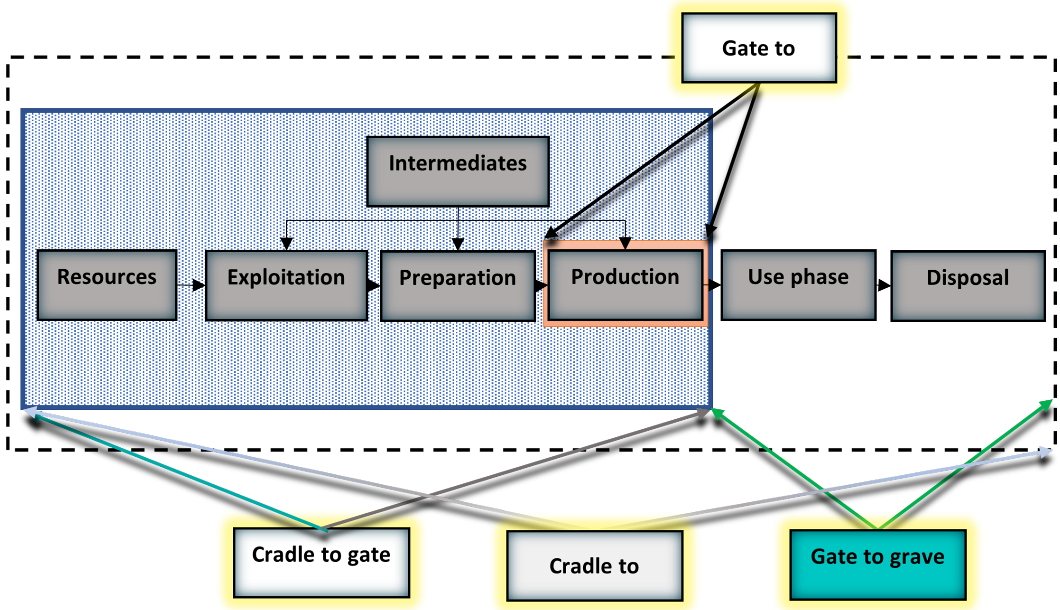

Figure 2. Different system boundaries for Life Cycle Assessment.

- Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the gate of the factory (i.e. before it is transported to the consumer). Cradle-to-cradle (C2C) is a particular kind of cradle-to-grave approach, where the end-of-life disposal step for the product is a recycling process. It is a method used to minimize the environmental impact of products by employing sustainable production, operation and disposal practices, and it aims to incorporate social responsibility into product development (ISO 14044:2006).
- Gate-to-gate is a partial LCA method, looking at only one value-added (unit) process in the entire production chain. Gate-to-gate modules may also later be linked in their appropriate production chain to form a complete cradle-to-gate evaluation (Jiménez-González et al., 2000).

2. Inventory Analysis is to identify and quantify energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges). It is a technical process of collecting data in order to quantify the inputs and outputs of the system, which control accuracy of the LCA. Energy, water consumption, row materials consumed, solid waste produced, emissions are calculated for the entire life cycle.
3. Impact Assessment is to assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis. This step includes obligatory and optional sub-phases: classification, characterization, normalization and weighting consistent with ISO standards. The quality of data obtained in the previous step is a key issue for this assessment. Depending on the selected software (i.e. SimaPro, GaBi, Umberto), the impact assessment methods are different. Impact assessment methods can:
   a) focus on a single impact or environmental footprint such as the carbon footprint or the water footprint, or
   b) include several impact categories such as: climate change, human toxicity, land use, or eutrophication or damage categories: Human Health, Ecosystem Quality, Resources.

IPCC (2022), developed by the International Panel on Climate Change, is a commonly used method. This single issue method lists the climate change factors of IPCC with a timeframe of 100 years and expressed the LCA results in terms of kg CO_2-eq.
ReCiPe 2016 was developed by the Dutch research institute of RIVM (National Institute for Public Health and the Environment), Radboud University Nijmegen, Leiden University and Pré Consultants in 2008. It is a midpoint and an endpoint method, and it considers three different cultural perspectives: individualist (I), hierarchist (H), and egalitarian (E). The method assesses several midpoint impact categories and the three areas of protection: human health, ecosystem quality, and natural resources at endpoint level.
IMPACT+ (IMPact Assessment of Chemical Toxics) is an impact assessment methodology originally developed at the Swiss Federal Institute of Technology – Lausanne (EPFL). The methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows) via 14 midpoint categories to four damage categories: Human Health, Ecosystem Quality, Climate Change and Resources (Figure 3).

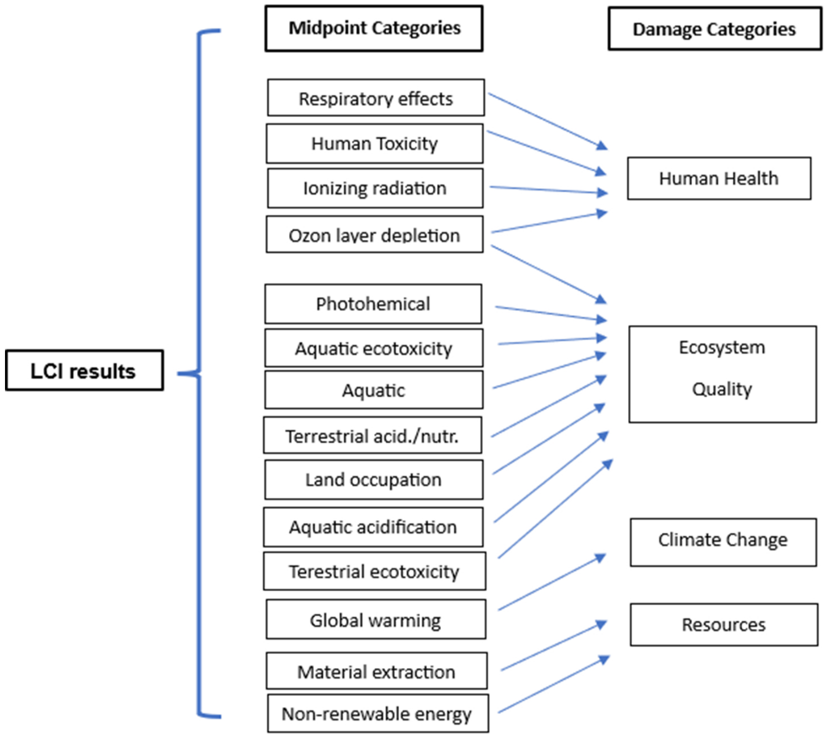

Figure 3. Overall scheme of the IMPACT 2002+ framework, linking LCI results through the midpoint categories to damage categories (Jolliet et al., 2003).

CED (Cumulative Energy Demand), is a methodology to assess and evaluate the sustainability of a single product or a service based on energy. It describes the total quantity of primary energy which is necessary to produce, use and dispose a product.

CML-IA, is a LCA methodology developed by the Center of Environmental Science (CML) of Leiden University in the Netherlands. This method elaborates the problem-oriented midpoint approach and provides a list of impact assessment of obligatory impact categories such as eutrophication, ionization radiation, aquatic ecotoxicity, land use, and human toxicity.

4. Interpretation is to evaluate the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results. The interpretation involves review of all LCA stages to check the data quality in relation to goal and scope of the study.

3. APPLICATION OF LCA ANALYSIS TO REDUCE ENVIRONMENTAL LOAD

Nowadays, LCA analysis is widely applied as an input to early stage of design (Agudelo et al., 2014), as well as for re-design and replacement of conventional materials to reduce environmental load (Klöpffer and Grahl, 2014). Redesign refers to activities that are aimed to reduce environmental load of particular stage of product's life and future post-use stage (Suhariyanto et al., 2018). So far, a number of LCA analysis have been carried in different applications, such as buildings or engineering constructions (Cabeza et al., 2014; Meex et al., 2018; Ryberg et al., 2021), electronic (Andersen et al., 2014; Bhakar et al., 2015; Nunes et al., 2021), photovoltaic solar panels (Corona et al., 2017; Ziemińska-Stolarska et al., 2021), wind power plants (Doerffer et al., 2021; Piotrowska and Piasecka, 2021), as well as services such as: parcel delivery from electronic shopping (Matuštík and Kočí, 2020) or public transport: bus and bike-share system (Wang et al., 2021).

Given the urgency of environmental issues, much research is carried out to substitute aggravating materials in different technologies. Selected cases can be seen in Table 1, where key aspects of replacement material supported by LCA analysis are presented.

3.1. Examples of replacement of the materials in chemical and biochemical industry

From an environmental perspective, the innovative chemistry solutions are mostly needed in polymer industry (Ojeda, 2013; Walker and Rothman, 2020). Fridrihsone et al. (2020) compared the environmental load of two raw materials for polyurethane (PU) production: polyols synthesized from rapeseed oil and petrochemical polyol. The results obtained for pilot-scale polyol synthesis proved that bio-based oil showed better environmental performance in 8 of 18 evaluated ReCiPe (Ecoinvent database) midpoint impact categories. The substitution of petrochemical compounds by bio-based oil in polyols production can lead to notably lower GHG emissions, non-renewable energy use and water consumption. However, for land use, ecotoxicity and marine eutrophication categories the bio-based polyols performed worse. To present complete information about environmental sustainability of bio-based PU production, the cultivation of rapeseed plants Northern European region was also subjected to LCA analysis (Fridrihsone et al. 2018). Corbière-Nicollier et al. (2001) used the LCA to prove the environmental advantages of biomaterials over glass fiber as reinforcement in plastics. The authors found that China reed biofiber is a suitable material to reduce environmental load of transport pallet, as confirmed by several indicators. Non-renewable energy demand for reed fiber (RF) pallets was significantly lower in comparison to glass fiber counterparts, especially due to low energy consumption in production stage of reed fiber and higher amount of RF in relation to polypropylene used. Additionally, the pallets made of bio-fibers had lower weight, which reduced fuel consumption during transport. The results showed also that reed fiber pallets emit to water and air generally less pollutants than glass fiber pallets. Only the emission of heavy metals to soil was higher for life cycle of reed fibers, which is associated with agronomic production. The major disadvantage of substitution glass fiber by bio-based materials was land utilization. As authors mentioned, the production of one reed fiber pallet requires about 52 m^2 of area for plant cultivation.

Holmquist et al. (2021) used LCA methodology to provide decision support to outdoor garment manufacturers in the substitution of fluorinated durable water repellents (DWRs). DWRs are chemical mixtures, typically based on hazardous side-chain fluorinated polymers. The LCA analysis were performed for a shell jacket with five alternative DWR: DWR based on side-chain fluorinated polymers containing the C4F9 and C6F13 moiety, silicone- based DWR, hydrocarbon-based wax and a non-fluorinated DWR based on hyperbranched polymers, while C8F17 compound was selected as a point of reference. Looking at human toxicity non-cancer indicator, C4 and C6 DWRs fared better compared to C8 counterparts. Regarding the climate change indicator, DWR finishing stage was the main contribution in life cycle of the garments and was associated with combustion of natural gas and energy demand for this process for all investigated DWR alternatives. However, the wash frequency and DWR impregnation were the key parameters for garment environmental performance. The LCA results indicated that non-fluorinated DWRs were preferable to fluorinated counterparts.

LCA analysis was successfully applied to determine the environmental load of polymer matrix in food packing sector. The coffee jar lids made from a bio composite based on banana fibers and polylactide (PLA) were compared to petrochemical plastics by Rodríguez et al. (2020). As pointed by authors increasing banana fiber contribution in replacement of PLA may improve overall environmental performance of the bio composite lids. The main environmental hot spot of bio composite was the production of PLA, mostly associated with energy demand during plant raw material production. The authors claim that 40% of banana fiber combined with high density polyethylene (HDPE) blend is expected to perform best among all studied combinations of polymer matrix. Wheat gluten powder has also been investigated to replace conventional film in food packing. The environmental performance of new bio-based alternative was evaluated by comparison with low density polyethylene (LDPE) and polylactide (PLA) packaging film in 18 impact categories (Deng et al., 2013). The LCA results exhibited that gluten film is favorable from environmental perspective in 14 impact categories over PLA film. The favorable results over LDPE were associated with less impact on climate change and fossil depletion. Compared to previously mentioned research, land occupation category was the weakest point of the bio-alternative. Metal organic frameworks (MOFs) are an emerging class of porous coordination polymers with ever- growing potential in applications. The synthesis process of MOFs has inherent problems associated with large volume of toxic organic solvents and significant energy consumption (Reinsch et al., 2016; Thomas-Hillman et al., 2018). Luo et al. (2021) used LCA method to evaluate environmental performance of organic solvent elimination in pilot scale production of UiO-66-NH2 for carbon dioxide capture application. The results proved that an aqueous solution-based system (where water was using as the solvent and the cleaning agent) produced much lower environmental impacts compared to the traditional solvothermal system. Above all, substantial reduction of global warming potential (GWP) and cumulative energy demand (CED) was observed (close to 90% in comparison to solvothermal methods). Furthermore, techno-economic assessment (TEA indicator) indicated that the aqueous solution-based system is an economically favorable method in the production of UiO-66-NH2.

LCA methodology is widely applied as a decision-making tool not only for support replacement of raw materials in different products but also for alternative synthesis methods, processes and technology to reduce environmental load. Green synthesis is replacing the traditional methods, aiming to overcome the limitations of standard processes and eliminate toxic compounds with parallel good efficiency and environmental performance (Zhang et al., 2020). To evaluate the benefit of green synthesis of iron oxide nanoparticles (IONPs) in relation to the conventional methods, a life cycle assessment was performed by Patiño-Ruiz et al. (2021). The examined green synthesis was based on replacement of iron (II) salt precursor with plant extract and sodium carbonate. The synthesis of IONPs by coprecipitation methods was selected as the reference process. According to the results green synthesis of IONPs presented lower environmental load compared to traditional method in all investigated impact categories. However, the major environmental contribution of green synthesis was detected for ethanol and electricity usage, as well as marine aquatic ecotoxicity.

3.2. Examples of material replacement in transport industry

Increasing number of vehicles on the road has a significant impact on the natural environment. Following data from The World Counts (www.theworldcounts.com), almost 97 million of vehicles are produced every year and the total number of means of transport could be 2 billion by 2035. This is the reason to implement pro-ecological solutions in automotive sector.

In several comprehensive papers, the role of lightweight material for automotive industry has been investigated (Ferreira et al., 2019; Ganesarajan et al., 2022; Tisza and Czinege, 2018). Vehicle weight reduction is considered as a crucial element in the limitation of CO_2 emission and fuel economy improvement strategies (Mallick, 2010). The complete or partially substitution of workhorse materials in the automotive industry, like cast iron or low carbon steel, is a promising solution to increase vehicle environmental performance. The LCA methodology has been widely applied to evaluate environmental impact of automotive components through the overall life cycle (Lin et al., 2017; Tadele et al., 2020). The talc-reinforced polypropylene composite is a conventional material in vehicle parts; substitution of talc by Miscanthus biochar noted to be beneficial, not only in fuel consumption of vehicles but also in ecologically perspective (Tadele et al., 2020). Replacing talc-reinforced polypropylene composite by lightweight composite resulted in lower fuel consumption during the use phase of components, global warming potential and ecotoxicity. Kelly et al. (2015) used LCA methodology to determine environmental consequences of mass reduction in vehicles. The analysis included potential lightweight materials identified in the literature, like aluminum, magnesium, carbon fiber reinforced plastics (CFRP), and high-strength and advanced high-strength steels (HSS and AHSS) in comparison to conventional materials. To determine vehicle cycle GHG impacts associated with material replacement, both a part- and system-level approach was applied. The results indicate that replacing steel with newer steel alloys, like HSS or AHSS, has a positive effect on mass reduction and GHG emissions. CFRPs significantly reduce weight of the door frame but result in the largest increase of GHG. The LCA results demonstrated environmental performance of lightweight vehicle designs depending on replacement material, parts of car body and substitution ratios of each material.

Tires contribute significantly to the environmental load of vehicles by the depletion of natural resources and emissions into the atmosphere (Piotrowska et al., 2019). Based on data from a tire plant operating in Central Taiwan, the total carbon footprint of tire production for electric bicycle are 4.53 kg CO_2eq based on 1.2 kg tire of electric bike produced per year (Lin et al., 2017). Using the SimaPro 7.3 software, it was calculated that the largest share in CO_2 emissions was the raw material production stage, while the carbon black made the greatest contribution to these results. As the authors Lin et al. (2017) suggest, replacing carbon black with graphene can indeed reduce carbon footprint of tire production. Based on simulations, the reduction was 12% and 23% by using graphene to replace carbon black 75 and 100 wt.% respectively.

3.3. Examples of material replacement in construction industry

Concrete is one of the most frequently used materials in construction industry, and its production has a prominent impact on the environment (Wałach, 2021). Cement production is one of the main emitters of anthropogenic CO_2, apart from transport and energy generation. Manufacturing of cement is responsible for almost 8% of worldwide CO_2 emissions (Andrew, 2019; Teh et al., 2017). For this reason, a different alternative of concrete mixtures has been proposed. Recycled aggregates (RAs) have been a promising material to total or partial replacement. Nowadays, two possibilities of RAs are proposed: the use of concrete from construction and demolition waste and slag from metallurgical production (Collivignarelli et al., 2020). Faleschini et al. (2016) performed comparative LCA analysis for different concrete mixtures: natural aggregates and recycled aggregates coming from reinforced concrete demolition with different replacement ratios. According to the results, replacement of natural aggregates by recycled substitutes can reduce CO_2 emission by almost 59%. Other impact indicators, such as eutrophication, acidification, human toxicity, eco-toxicity and ozone layer depletion also proved that adapting recycled aggregates coming from construction and demolition waste might reduce environmental load of building sector.

Faleschini et al. (2014) evaluated also environmental impact of black/oxidizing electric arc furnace (EAF) – main by-product of steel manufacture, as replacement of traditional aggregate for concrete production. The results proved that simplicity of the RA processing system promotes more sustainable energy consumption and demand of fossil resources. Emission factors were evaluated both in direct and indirect way, linked to raw materials and productive system, respectively. According to the results, production of 1 ton of EAF determined a reduction of environmental impact by more than 40% with respect to natural aggregates for each examined category. The comparative LCA analysis of four different concretes made of RAs was published also by Colangelo et al. (2018). The following natural aggregates were compared: marble sludge, construction, and demolition waste (CDW), blast furnace slug and incinerator ashes, mixed with cement in the same mass proportions. The system boundaries were based on the production phase, as the most relevant stage in terms of environmental impacts. Compared to potential substitutes, the ordinary concrete had the greatest impact in all discussed categories. The mixture of concrete with CDW showed the lowest value of CO_2 emitted to the air, as well as other pollutants such as: aluminum, butane, nitrogen and sulfur oxides. LCA results clearly indicated that use of RAs can decrease the environmental load of a concrete production.

The LCA analysis was also successfully applied to evaluate environmental load of material and technologies in the production of asphalt mixtures. [10]Bressi et al. (2021) performed comparative LCA of traditional Italian asphalt mixtures and certain innovative mixtures containing different percentages of recycled materials, employed in the base course of flexible road pavements. The eleven different asphalt mixtures were compared: traditional mixture and 10 alternative mixtures with recycled materials (crumb rubber (CR) and reclaimed asphalt pavement (RAP) assuming various technological modification). The results showed that asphalt mixture with 40% of RAP in partial substitution of virgin aggregates significantly reduced the scores of all examined impact categories compared to the reference solutions. Additionally, the reduction of quantity of bitumen added to the mixture allowed further decreases in several impact categories, especially in the cases of the fossil depletion, human toxicity and marine ecotoxicity. The solutions containing RAP had also positive effect on reduction of primary energy demand. The contrary results were observed for CR mixtures, where energy required for production of these mixtures notably increased, especially when the devulcanization process was applied.

3.4. Examples of material replacement in electronics industry

Electronics industry is still a fast developing economic sector. Regrettably, this continuous progress despite countless benefits, is not free from risk related to environmental load (Clarke et al., 2019). In particular, short service life and low recycling rate of electronic equipment inevitably lead to growing amount of waste. Therefore, electronic waste is considered as fast expanding environmental problem, especially for developed countries (Abalansa et al., 2021). In the last years, LCA analysis has been frequently used to assess environmental load of electronic systems, often comparing them with upgraded solutions. Recently, Bovea et al. (2020) published a study investigating the best end-of-life scenario for household electronic devices based on LCA methodology. In the field of electrics and electricity, LCA analysis has been successful applied in household appliances (Dekoninck and Barbaccia, 2019; Hischier et al., 2020; Monfared et al., 2014), screens and displays (Amasawa et al., 2016; Bhakar et al., 2015), electronic elements (Pokhrel et al., 2020) or Internet and mobile phone networks (Ruiz et al., 2022; Scharnhorst et al., 2006). Many electronic components rely on critical raw materials (CRMs) as key elements, from light- emitting parts (REEs- rare earth elements, like Ce, Y, Eu), to screens (In), integrated circuits and circuit boards (PGMs- platinum group metals), primary batteries (Li), semiconductors (Ge, Ga, Si, Co, B) and electrically and thermally conductive material (graphite) (Bobba et al., 2020). Although such elements are used in low concentrations, mass production of novel technologies raises fundamental questions related to availability of particular raw materials in the near future (Knoeri et al., 2013; Weil et al., 2009). The growing trends in demand of those materials are to be expected due to large consumption of emerging technologies (Dolega et al., 2021). Moreover, the list of CRMs published by European Commission has increased significantly from year to year, now including 30 elements (European Comission, 2020). Consequently, the substitution of critical metals by other more readily available or less critical without decreasing product performance, became important challenge for the science community.

The environmental consequences of a material substitution decision can be successfully assessed with life cycle assessment (LCA) (Mancini et al., 2015). Lithium-ion batteries are already the most popular power source for modern consumer electronic devices (Xie and Lu, 2020). Environmental assessment of potential alternatives to Li-ion batteries have already been performed by Peters et al. (2016). The authors presented sodium-ion batteries (SIBs) with a layered oxide cathode in combination with a hard carbon anode. Therefore, SIBs consist of abundant and cheap elements, with Na instead of Li and Al instead of Cu. 1 kWh of storage capacity was used as a functional unit in applied LCA methodology. In comparison to the Li-ion batteries, SIBs show better results in such impact categories as freshwater eutrophication potential (FEP), human toxicity potential (HEP) and fossil depletion potential. Global warming potential (GW) with the value of 140.33 kg CO_2eq. testified also to the advantage of SIBs. However, nickel compounds as a precursor to the cathode production were responsible for relatively high impacts in several categories.

Similar design considerations were published by Monteiro Lunardi et al. (2017), who compared different perovskite/silicon (Si) tandem structure of solar cell with different metal contacts using LCA analysis. Three structures of perovskite/Si tandem solar cells were considered: with Au contact, with Ag contact on a hetero-junction silicon solar cell and with Al contact on a p-n junction silicon cell with ITO (indium tin oxide) as a transparent conductive layer. According to the results of EPBT, all the analyzed perovskite/Si tandem solar cell outperformed Si technologies due to their higher efficiency. The EPBT for perovskite/Si tandem Ag and Au was calculated assuming the efficiency of 27% whereas 24% for perovskite/Si tandem Al. Based on the results of all the impacts, the authors concluded that perovskite/Si tandem using Al as top electrode had better environmental outcomes in comparison to other tandem structures studied. However, the authors stressed significant impact of ITO layer on GWP and suggested, replacement of this material by FTO (fluorine-doped tin oxide) glass as proposed by Gong et al. (2015).

Replacement of ITO, as a conventional material used in liquid crystal displays, was also investigated by Arvidsson et al. (2016). LCA methodology was applied to analyze the environmental consequences of substituting ITO for graphene in two impact categories: life cycle energy use and life cycle use of scarce metals. In the study, emission-based impact categories were not included due to early stage of graphene electrode technological development. Results proved that the energy use for graphene production was about three times lower compared to the ITO production; 63% of the load was generated by methane production whereas 15% by applied deposition methodology (Chemical Vapor Deposition – CVD). Regarding scarce metal use, the copper use in graphene production is about 300 times higher than the use of indium in ITO production. The authors concluded that while copper availability is not currently at risk, metal use cannot continue forever and finally reduction of net copper use is nevertheless advisable in chemical vapor deposition process.

Kawajiri et al. (2022) performed an LCA analysis for the substitution of ITO by aluminum-doped ZnO (AZO) films in the liquid crystal displays (LCD). To evaluate the environmental impact of material replacement, the authors propose a new methodology called the scenario difference method (SDM). This approach involves replacing the old material with a new one in the inventory data of the original system, which eliminates the step of collecting data for substitute materials. The results proved that replacing ITO with AZO can reduce the total environmental burden of LCD. However, cradle-to-gate greenhouse gas (GHG) analysis showed that emissions from AZO were larger than those from ITO.

The environmental impact of alternative material and production methods for printed circuit board (PCB) were studied by Nassajfar et al. (2021). PCB is the crucial element in most electronic products and devices. A typical PCB consist of dielectric layer (flame retardant FR4 composite) and conductive material (copper) laminated with several layers of prepreg and copper foil. In general, acquisition of raw materials used to produce conventional PCB requires a large amount of energy derived from non-renewable resources. For this reason, the authors investigated three alternatives for a typical PCB substrate: polyethylene terephthalate (PET), polylactic acid/glass fiber (PLA/GF) composite and paper. The presented LCA analysis also included a comparison of conductive materials: copper and electrically conductive adhesive containing silver nanoparticles (Ag NPs). Results proved that replacement of copper with Ag NPs in conductive materials decreased the environmental impact of PCB in all discussed indicators. Additional replacement of the FR4 composite with other alternatives resulted in a significant reduction of global warming potential (GWP) and abiotic depletion potential.

QLED displays are emerging technology which uses quantum dots (QD) as a light source. The most common in the commercial market is cadmium-based QD. However, due to possibility of releasing the toxic Cd from the core of nanoparticles, Cd-QDs have raised a great concern (Chen et al., 2012). Chopra and Theis (2017) published a comparative LCA of Cd-QD and In-QD-enabled displays. The values of cumulative energy demand indicator showed that synthesis of In-based QD was more energy demanding whereas core enrichment step was responsible for highest primary energy consumption. As the authors concluded, despite increasing demand for less toxic products, investigated synthesis of In-QD was not an environmentally preferable option from cradle-to-gate perspective.

Selected case studies of comparative LCA analysis for replacement materials to reduce environmental load are shown in Table 1.

4. CIRCULAR ECONOMY AND LIFE CYCLE ANALYSIS

The concept of linear economy (LE) based on the principle "buy, use and throw away" – a straight line from raw material extraction to product use and its final landing in landfill or incineration plant is still the norm in our economy. However, the importance of applying the CE, where materials can be used again and again, just closing the resource loops becomes more urgent nowadays. Implementing CE strategies is a useful tool for enhancing the world's sustainability. The circular economy aims to reduce the amount of waste generated in production and distribution processes and strengthens the link between CE and waste management, effectively contributing to waste reduction. Strategies in a circular economy are described in Table 2.

The LCA methods consider several different environmental impacts such as carbon footprint or water footprint and use of resources. The LCA study shows in general how the environmental load can be avoided, but only the 'cradle-to-cradle' (C2C) approach goes a step further and ensures that all materials used in production can be reused as nutrients in the biological cycle or as substrates in the technical production cycle. The adapting of the C2C approach to the CE allows for a quantitative assessment of environmental risks and enables a much better assessment of the circularity of materials than the qualitative indicators typically used in the CE implementation.

LCA is a crucial assessment methodology to inform and improve CE strategies by comparing them in terms of sustainable performance. A very interesting critical comparative analysis of the sustainability of CE indicators and the LCA method for assessing the circularity of glass and plastic (PET) bottles was conducted by Lindgreen et al. (2021). The authors chose various quantitative circularity indicators e.g., the

Table 1. Examples of case studies of comparative LCA analysis for replacement materials to reduce environmental load.

Object of analysis	System boundaries	Functional Unit (FU)	Methods	Indicators	Reference
		Packing industry			
Petrochemical feedstock and vegetable oil to synthesize polyols for polyurethane production	Transport, synthesis, energy use	1 kg of rapeseed oil-based polyol, capable of being used to make spray applied PU coatings and rigid PU thermal insulation foams	ReCiPe Endpoint; Midpoint; Cumulative Energy Demand.	Global Warming Potential (GWP), GHG emissions, ReCiPe impact categories	Fridrihsone et al. (2020)
Biocomposite based on banana fibers, PLA and petrochemical plastic (high density polyethylene -HDPE) as a materials for coffee jar lids made	Banana agriculture, fibre production, fibre transportation, fibre preparation, lid production, lid use, and lid disposal	To cover a glass jar (53 mm diameter) and preserve the coffee stored in the jar without any sign of deterioration of coffee freshness during 1 year of storage	ReCiPe, midpoint	ReCiPe impact categories	Rodríguez et al. (2020)
Gluten-based film and PLA and LDPE film as a material in food packing	Cultivation and harvesting of wheat, gluten production, use of gluten film	1 kg wheat gluten produced)	ReCiPe Endpoint; Midpoint;	ReCiPe impact categories	Deng et al. (2013)
China reed fiber and glass fiber as a reinforcement in plastic	Production, transport, use and elimination	Standard transport pallet satisfying service requirements (transport of 1000 km per year) for 5 years	CML, Eco indicator 95, Ecopoints	Emissions to water, air and soil, renewable and nonrenewable raw materials needed, non-renewable energy consumption	Corbière-Nicollier et al. (2001)
Alternatives for fluorinated DWRs in outdoor garment: C_4F_9PFAAS, C_6F_{13} PFAAS, silicone- based DWR, hydrocarbon-based wax and a non-fluorinated DWR based on hyperbranched polymers	Manufacture, use phase and end of life in cradle to grave perspective	Keeping the wearer warm and dry during one use of jacket (30 min)	USEtox CFs, ILCD PEF v. 1.09	Human toxicity CFs, acidification, climate change, eutrophication, ozone depletion, primary energy, resource depletion and water use	Holmquist et al. (2021)
Elimination organic solvents in production of UiO-66-NH_2 (MOF)	Chemical and energy consumptions associated with the raw material extraction and processing for material production in cradle to gate perspective	1 kg of UiO-66-NH_2 on a dry basis	ReCiPe Midpoint	Techno-economic assessment (TEA), cumulative energy demand, global warming potential, particulate matter, terrestrial acidification, freshwater eutrophication, human toxicity, water scarcity	Luo et al. (2021)

Table 1 continued

Object of analysis	System boundaries	Functional Unit (FU)	Methods	Indicators	Reference
Green synthesis of iron oxide nanoparticles	Raw materials and production stage in cradle to gate perspective	Production of 1 g of iron oxide nanoparticles	CML-IA method	Abiotic depletion, fossil fuels, global warming potential, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, terrestrial acidification, eutrophication	Patiño-Ruiz et al. (2021)
		Transportation sector			
Miscanthus biochar (MB)-reinforced polypropylene composite an conventional talc-reinforced polypropylene composite for automotive applications	Miscanthus cultivation, MB production, talc production, PP production, composite manufacturing transport of required inputs, use phase, and end-of-life (EOL) phase	Automotive component that requires 982 cm^3 of composite material	TRACI v2.1	TRACI impact categories	Tadele et al. (2020)
Rubber tire for bicycle with carbon black and graphene	–	Raw materials, production, transportation, storge, uses and final treatments	PAS 2050	Inventory of carbon footprint	Lin et al. (2017)
Traditional mixtures of asphalt and 10 alternative mixtures containing different percentages of crumb rubber (CR) and reclaimed asphalt pavement (RAP)	Resources extraction and composite materials production, transportation of materials, construction equipment operation during the construction of the base course	1-km-length principal Italian rural roadway, located in Empoli (Tuscany) with 2 carriageways and 4 lanes and a base course which is 10 cm thick and 15 m wide	ReCiPe at midpoint level	Climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, marine eutrophication terrestrial acidification, ozone depletion, terrestrial ecotoxicity and water depletion	Bressi et al. (2021)
Lightweight materials (CFRP, HSS, AHSS, aluminium, magnesium) to replace steel in vehicle parts	All processes related to vehicle manufacturing	Depending on the scope of analysis from the part (kg CO_2e/part) to the system (kg CO_2e/system) to the full vehicle lifetime (kg CO_2e/260,000 km vehicle lifetime)	GREET approach	GHG emissions	Kelly et al. (2015)

Table 1 continued

Object of analysis	System boundaries	Functional Unit (FU)	Methods	Indicators	Reference
Construction industry					
Production of two concretes based on: EAF slag and reference one made with traditional aggregates	Extraction and processing of raw materials and production	1 ton of aggregate	CML 2002 Method	Climate change, eutrophication, acidification, photo-oxidant formation, human toxicity, eco-toxicity and ozone layer depletion	Faleschini et al. (2014)
Natural aggregates (NA) and reinforced concrete demolition (RCA) with different replacement ratios (0,20,35%)	For NA: extraction of raw materials, transportation, aggregates processing. For RCA: construction and demolition waste delivery and storage, volumetric reduction, transportation, aggregates processing.	1 t of aggregate	CML 2002 Method	Climate Change, Eutrophication, Acidification, Photo-Oxidant Formation, Human toxicity, Eco-toxicity and Ozone Layer Depletion	Faleschini et al. (2016)
Comparative four mixtures of recycled aggregates in concrete production	Production phase (processing of raw materials, transportation, and production of concrete)	1 m^3 of concrete (with a specific weight equal to about 2400kg/m^3) to facilitate data management and application.	Eco-indicator 99	Air and land emissions, 11 impact categories	Colangelo et al. (2018)
Electronic industry					
Sodium-ion batteries as potential alternatives to lithium-ion batteries	Production process in cradle-to-gate perspective	1 kW h of storage capacity	ReCiPe, midpoint level	Fossil depletion potential, global warming potential, terrestrial acidification potential, human toxicity potential, fresh water and marine eutrophication	Peters et al. (2016)
Three perovskite/Si tandem cell structures using silver, gold and aluminum as top electrodes compared with p–n junction and hetero-junction with intrinsic inverted layer Si solar cells	Raw material, cell production, module assembly, use, end of life, landfill	1 kWh of generated electrical energy over the lifetime of the module	–	Global warming potential, human toxicity potential (cancer and non-cancer effects), freshwater eutrophication potential, freshwater ecotoxicity potential and abiotic depletion potential, EPBT	Monteiro Lunardi et al. (2017)

Table 1 continued

Object of analysis	System boundaries	Functional Unit (FU)	Methods	Indicators	Reference
Substitution ITO layer with graphene in LCDs application	Production process in cradle-to-gate perspective	Layer with a surface area of 1 cm^2	–	Life cycle energy use, life cycle use of scarce metals	Arvidsson et al. (2016)
Substitution of ITO by AZO in an LCD TV	Raw material production, production of target substrate, production of transparent electrode, usage, and recycling stages in cradle-to-grave perspective	32 inch LCD panel	LIME2	Global warming potential, ozone layer depletion, acidification, air pollution, photo chemical oxidant formation, human toxicity cancer, human toxicity non cancer, aquatic toxicity, terrestrial toxicity, eutrophication	Kawajiri et al. (2022)
Alternative materials for PCB production (PET, PLA/GF and paper)	Raw material acquisition, manufacturing and waste disposal of PCBin cradle-to-grave perspective	1 $m^2$of four-layer PCB	CML 2001-August 2016	Abiotic depletion potential (fossil), acidification potential, eutrophication potential, freshwater aquatic ecotoxicity potential, global warming potential, human toxic potential, ozone layer depletion potential, photochemical ozone creation potential, terrestrial ecotoxicity potential	Nassajfar et al. (2021)
Cd-QD and In-QD as a material for QLED displays	Raw material, synthesis and incorporation in LCD displays in cradle-to-gate perspective	Three FU for different manufacture stage: (1) 25 mg of QD core/ shell/shell material, (2) g of QDs embedded per mm2 of display area, (3) entire market segment	–	Cumulative energy demand	Chopra and Theis (2017)

Table 2. Strategies in a circular economy (Potting et al., 2017).

Smarter product use and manufacture	Refuse	Make a product redundant: abandon function or use different product
	Rethink	Make product use more intensive: sharing or multi-functional products
	Reduce	Consume less through efficient manufacturing or use
Extend lifespan of products	Re-use	Re-use of functioning discarded products by another use
	Repair	Repair and maintenance of defects to keep an original function
	Refurbish	Restore and update
	Remanufacture	Use parts in a new product with the same function
	Repurpose	Use parts in a new product with a different function
Useful application of materials	Recycle	Process materials to obtain the same or lower quality
	Recover	Incineration of materials with energy recovery

Material Circularity Indicator (MCI) – which measures how much linear flow has been minimized and how much restorative flow has been maximized, or the Material Reutilisation Score (MRS) – which includes two variables % recyclable product and % recycled content in the product, and several other indicators. As expected, analysis of the CE indicators has shown that a glass bottle has a significantly higher circularity than a PET bottle. However, when the LCA was applied to both packings, the PET bottle shows the lowest potential environmental impact. This was due to the much higher contribution of the glass bottle production process to global warming. Therefore, although the glass bottle can be considered the best packaging in terms of CE efficiency, the LCA analysis showed that the negative environmental impact of glass production is much higher than that of PET bottles. This means that, depending on the type of circularity indicator of a product that meets the CE requirements is also not always environmentally preferable, as indicated using LCA methods. This type of problem of choosing between circularity and environmental impact can cause problems in corporate decision-making processes.

Spreafico (2022) analyzed 156 selected case studies of comparative LCA, extracted from 136 articles, where the environmental impacts of design solution for CE are compared with those of other solutions were waste is not exploited. The author evaluated the different design strategies for CE and hierarchized them based on environmental sustainability of the solutions. He tested different design strategies for CE with the aim to overview them. The considered CE options were reducing waste, using renewable energies, reuse, remanufacturing, recycling, energy recovery, disposal, transforming waste to energy. He concluded that design for remanufacturing produced the best option with impact reduction by 53%, followed by design for recycling 45%, while design for energy recovering from waste was the worst option.

By combining CE principles with LCA methodology, product designers can quantify the environmental performance of different product and supply chain configurations, compare circular strategies, and ensure positive environmental impacts. Unfortunately, the LCA does not provide insight into how a product or technology will perform in the future. LCA can assess the environmental impact of a product and/or process, but its results do not currently indicate how circular a solution is. Thus, quantitative circularity indicators may fill this gap. These complementary indicators can measure the circularity of resources and material flows in LCA. It is therefore necessary to develop an integration of CE and LCA.

5. CONCLUSIONS

In summary, LCA is an important tool to quantitatively assess environmental performance and impact and should be closely linked to CE strategies. Incorporating LCA, especially the C2C approach allows a comprehensive assessment of a product, service or process.

By combining principles of CE with LCA methodologies, product designers and developers can quantitatively assess the environmental performance of various products and compare circular strategies to ensure a positive environmental balance from the design of new circular products or services.

There are several opportunities to integrate LCA into a CE strategy, where LCA with the C2C implementation can play a key role in the development of quantitative indicators for CE in relation to a designed product. LCA enables an environmental assessment of that product and its life cycle and this will provide quantifiable evidence to support decision-making.

There is a need for improvement of existing solutions, developing the intersection between the circular economy and LCA, mainly searching for efficiency gains rather than supporting new designs. Properly defined circularity indicators are key to a successful circular transition.

6. SUGGESTIONS FOR SUSTAINABLE FUTURE

- Improvement of sustainability awareness of society by enhancing education for sustainable development by both teaching and learning.
- Incorporating LCA methodology in engineering education, because all new EU research projects must include LCA of any new product or process.
- Transformation of linear economy to circular one is an unavoidable necessity in near future if we want to avoid an ecological disaster caused by global warming.

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