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REVIEW PAPER

Life-cycle Assessment – An Overview for Environmental Research

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ABSTRACT

Life-cycle Assessment (LCA) is a standardized approach or technique to evaluate the potential environmental impact of a product or service over its entire life-cycle. It aims to measure the environmental impacts that arise from the raw materials and resources used and released, through a product or service's life-cycle. In this review paper, our objective is to offer a thorough examination of LCA, encompassing its various components and its extensive applications within the realm of environmental research. LCA facilitates the identification and quantification of environmental repercussions of human activities, enabling a subtle analysis of the sustainability advantages and inherent trade-offs embedded within intricate systems. LCA is a decision-making tool which assist us in making informed decisions and optimize technical solutions to reduce the environmental impacts due to increasing anthropogenic activities. LCA is a systematic analysis that provides us with reliable and comprehensive information to formulate strategies and implement policies to improve the sustainability of our products, combat challenges and enhance our awareness of any environmental implications resulting from our environmental research studies.

HIGHLIGHTS

- Environmental Impact Assessment.
- Policy Recommendation for Implementation.
- Application in Organizational Sustainability.
- Comprehensive Examination of Pros and Cons.
- Opportunities for Enhancing Product Sustainability.
- Methodological Framework for Future Environmental Research.

Keywords: Environment, LCA, Case studies, CBA, Research, Impacts

The Life Cycle Assessment (LCA) is a systematic, standardized method used to determine the potential environmental impact of a product or service through its life-cycle (Ciacci and Passarini 2020), from the extraction of the raw materials (e.g., mining for oil), processing of the materials, product manufacture, distribution of the product/ service, and usage through the product/ service's entire life (Fig. 1). It is a useful method that may be used to contextualize the environmental effects of environmental research in comparison to alternate remedies or material alternatives. LCA takes a comprehensive approach that includes extraction of raw materials and the manufacturing process to transportation, utilization, and eventual disposal. This comprehensive approach serves to broaden our comprehension of the environmental ramifications associated with a product, going beyond what is immediately apparent and evident. LCA offers the capability to pinpoint specific areas in need of enhancement, comprehend and evaluate trade-offs among different materials, and serves as a

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valuable tool for proactively averting environmental challenges(Miller, 2022). LCA helps organisations to make informed decisions on technological solutions to mitigate environmental issues due to increasing anthropogenic activities. For example, human activities on land and in water can have a significant impact on terrestrial and aquatic ecosystems. The largest contributing activities include those through pollution, and overexploitation of ecosystem goods and services, such as overuse of medicinal plant species, and producing an excessive amount of carbon, more than the environment's sequestering ability. Among the many issues confronting ecosystems are climate change, habitat loss and air pollution (Statistics Canada, 2013). While it's inevitable that inventions and socio-economic advancements will persist, it's equally crucial to ensure that these innovations and enhancements have the least possible environmental impact which can potentially be achieved through the application of Life-cycle.

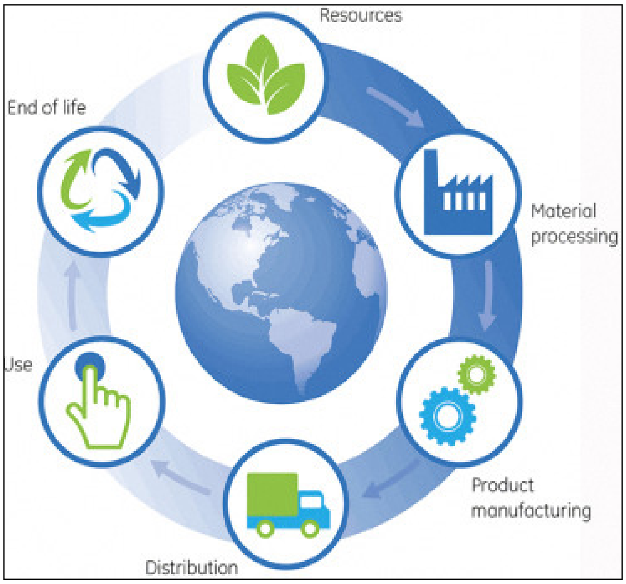

Fig. 1: Components of life-cycle analysis (Brusseau, 2019)

The principal objectives of majority of the environmental research are to improve environmental sustainability by mitigating climate change effect, increase carbon sequestration and improve and conserve biodiversity and ecosystems. To achieve these, several solutions are often implemented without due consideration for various crucial factors. These factors encompass resource utilization, the overall cost associated with the program, and, perhaps most importantly, the potential environmental repercussions that may emerge in the process. Such oversight can inadvertently exacerbate existing environmental issues. One illustrative case of "sustainable solutions" that inadvertently yield detrimental environmental outcomes pertains to the adoption of biodegradable or recyclable disposable materials as alternatives to conventional lower-grade plastics in the paper industry. In Recent times,in view sustainability, there are many Food and Beverage enterprises encouragingthe use of biodegradable cutleries. However, majority of these disposables are disposed of in general waste bin without being sorted for their recyclability, or biodegradability for composting use before being sent for incineration and hence, their recyclability and compostability/ biodegradability become redundant thus, making the low-grade plastic a better option as they are much less resource intensive during their production stage as compared to the paper-made, biodegradable, or high-grade plastic disposables (TED-Ed, 2020). Conversely, this can result in a heightened environmental impact, whereby the proposed solutions inadvertently contribute to the very problems they were intended to address. Therefore, LCA is applied to provide a framework for a detailed and systematic analysis of the damage that a product or process can cause to the environment. LCA can be used to understand the complete extent of impacts from a single product or to compare the resource extent and impact of numerous products. It is used to assess all aspects of a subject, from raw feedstock extraction to end-of-life or it can focus on certain segments of a supply chain, such as the environmental implication before a product reaches the market or an idea is implemented (Miller, 2022).

The aims of this review paper are twofold: firstly, to elucidate the central purpose and methodologies associated with LCA; and secondly, to serve as a valuable resource for individuals seeking to acquire knowledge and skills in the application of LCA to their products or services, especially within the context of environmental research. This comprehensive review aims to shed light on the pivotal role that LCA plays in pinpointing avenues for enhancing the sustainability of products or services. Furthermore, it seeks to demonstrate how LCA can be an invaluable tool for organizations, empowering them with the insights needed for informed decision-making in support of more promising and efficient environmental initiatives and projects.

CONCEPT AND FRAMEWORK

The four iterative phases of LCA are Goal definition and scope, Life-cycle inventory assessment, Impact assessment and life-cycle interpretation (Jolliet *et al.* 2016).

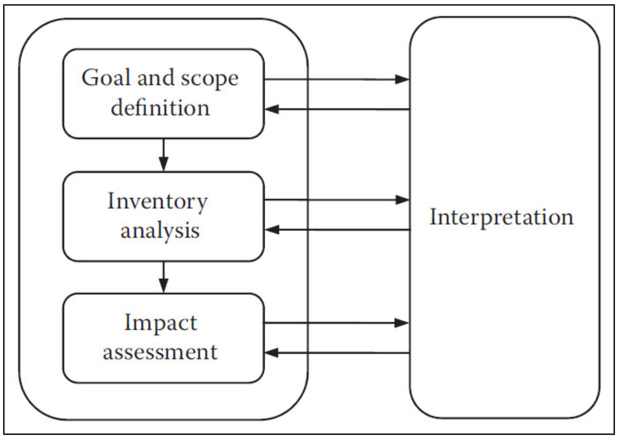

Fig. 2: The four iterative phases of life-cycle assessment (Jolliet *et al.* 2016)

These elements assist in analysing the environmental impact of a research program. This method is commonly used as it's a standardised methodology provided by the International Organisation for Standardisation (ISO), making it a reliable technique. The two main ISO standards for the LCA are ISO14040 and ISO 14044. Direct applications of the method include product development and improvement, strategic planning and public policy making.

1. Goal and scope examine the objective of the assessments, the boundaries of this LCA, the environmental impacts involved in the assessment and the data that will be collected (Miller, 2022).
2. Inventory analysis analyses the life-cycle of the assessment, which includes the examine of the materials and resources used and the waste and environmental emissions generated (Burnley *et al.* 2019).
3. Impact assessment measures the environmental effect of the activities that took place in the assessment by taking into account the material, energy and emissions data gathered during the inventory phase to quantify the environmental impacts.
4. Interpretation phase where the overall findings of the study are discussed, which clarifies the findings and draws attention to the hypothesis and constraints. In order to best fit the assessments to their particular goal, the LCA steps are carried out frequently (Miller, 2022).

Environment research studies are done with the aim towards sustainable development –"development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN Sustainable Goals, 2016). Examples of sustainable developments include solar and wind energy, green buildings or sustainable construction, sustainable agriculture, water efficient fixtures, green spaces etc. Environmental research includes studies that are under the topics of climate change, renewable energy, conservation biology, noise pollution, geographic information systems, urban ecology, etc.

Environment research investigates the cause-and-effect of the impact of human actions on terrestrial and aquatic ecosystems and their resilience. The outcomes help planners to better develop and construct buildings and other modules to help to improve the use of water resources and the efficiency of land use. Environmental research frequently combines several interdisciplinary fields of study to achieve a single objective. Other fields include chemistry, geology, geo sciences, soil sciences, hydrology, ecology etc. Focusing solely on a single objective can sometimes lead us to overlook the adverse environmental impacts stemming from our initiatives. As a result, LCAis considered indispensable in preventing unwarranted harm to the environment.

Environmental research can further enhance sustainable developments through LCA by examining the resources used throughout the life of these developments and redefine how we can use this knowledge to make these developments better. For example, construction can be made more sustainable by recycling used old materials from buildings that have been previously torn down, which eliminates the need to dispose of the unwanted material through incineration upon end of life, which process consumes a significant amount of energy and incurs substantial expenses. Furthermore, this can be improved further by mixing better quality building materials, such as bamboo reinforced concrete, which is a special construction material specially engineered for sustainable development, which improves the quality of the infrastructure, and prolongs its "use' stage. Hence, this example indicates how important it is to improve our current building and production strategies by recounting their resource extensivity.

The following section highlights the benefits and limitations of LCA methodology as well as the possible errors that may arise from the handling of data for the assessment.

LCA METHODOLOGY

Goal definition & scoping

In this first step, the following questions need to be addressed.

What will be assessed? What kind of product/ service? What system boundary is used? What impact categories are we focusing on? What are the intended outcomes?

These questions help to solidify the goal and assist the auditor to define and keep track of their scope. The stage of goal and scope definition ensures that the LCA is carried out consistently. A LCA analyses the life-cycle of a product, service, or system. A model is a simplified version of a more complex reality. As with every simplification, the reality will be influenced in some way. The issue for an LCA practitioner is to ensure that the simplifications and distortions do not have a significant impact on the outcomes. The simple method to accomplish this is to thoroughly define the goal and scope of the LCA. The aim and scope define the most critical decisions, which are frequently subjective. The purpose of the LCA is to provide a detailed characterization of the product and its life-cycle, and a description of the system boundaries (Golsteijn 2022).

The system boundaries define what elements to be included in the assessment. Substances that contribute little to the total footprint can be excluded from the scope of the analysis. As a result, the system boundaries preclude this (Golsteijn 2022). A few types of system boundaries are—

- Cradle to grave - from the extraction of raw materials to manufacturing the product/ service (e.g., mining of oil) to the disposal (e.g., incineration).
- Cradle to cradle - the lifecycle of a recycled product, from getting the raw materials from used old products (e.g., cotton from old clothes) to the disposal of the product at a recycling centre (e.g., cotton recycling centre).
- Cradle to gate - where the life-cycle starts at the raw material extraction, but only ends at the factory gate, also known as the packaging stage.
- Gate to gate - is where there is only one process in the production chain (e.g., manufacturing to packaging) is being focused on.

Impact categories, which are the quantified forms of different environmental impacts, consisting of three broad damage categories - environmental impacts, resources used during the respective life stage of the product and waste type that has been produced throughout the life stage. Impact categories indicate the environmental issues that may be the result of the research program.

Three levels exist to gauge the comprehensiveness of an LCA, based on technical details: conceptual, simplified and detailed (Farjana *et al.* 2021). Different types of LCA are used to either give a brief description, a summary or give concise information on the environmental inputs and outputs of a product.

- **Conceptual LCA:** gives a simple looking qualitative inventory, where flow charts give a fundamental understanding of the main environmental impacts. The results can be used for qualitative reporting of assessment results, but not for corporate marketing or explicit publication of LCA study(most simplified model).
- **Simplified LCA:** gives a slightly more comprehensive overview, where basic data is involved, and generic standard modules are given.
- **Detailed LCA:** a fully comprehensive report with detailed considerations of each life-cycle stage. It has system specific datasets & analysis is done in detail for further process improvement.

Inventory analysis

'Inventory' refers to the processes mentioned earlier, such as raw material production, material processing, end of life etc.; and these processes can be thought of as a life stage, like the life-cycle of a butterfly. The inventory analysis considers all environmental inputs and outputs linked with a product or service. The utilization of raw materials and energy is an example of an environmental input (something taken from environment to put into the product's life-cycle), whereas emission into the environment during product's life-cycle which include contaminants and waste streams are examples of environmental outputs (Golsteijn 2022).

The Fig. 2A illustrates an instance of an inventory analysis within the context of a conceptual LCA.

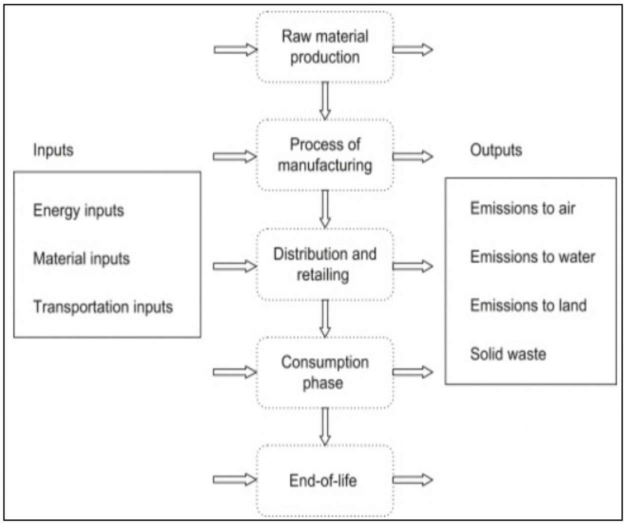

Fig. 2A: typical process flow diagram with generalized unit processes (Muthu, 2020)

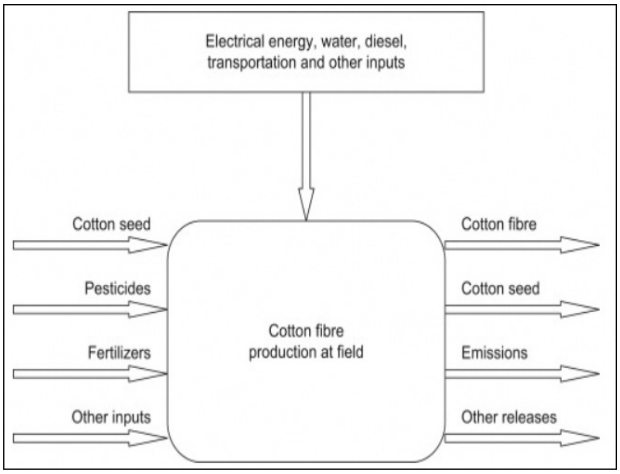

Fig. 3: Inventory analysis of a textile industry, producing cotton fibre (Muthu, 2020)

Impact analysis

In this step, the impact categories are analysed to understand the impacts of the resources used in the product/service and their emissions produced. The life-cycle impact analysis allows the organisation to develop findings that will help it make better business decisions, where categorization and translation of the environmental implications of all processes collected and modelled in the life-cycle impact analysis into environmental topics such as global warming or human health (Golsteijn 2022). The resources used also refer to the environmental input, while the emissions also refer to the environmental output. Subsequently, these impacts, referring to the consequences of the resource intensity and the resultant effects of emission, are sorted and ranked in terms of importance and priority to the organisation and the relevant stakeholders. Sorting and ranking are employed to grant stakeholders the opportunity to express their preferences regarding which aspects they would like to prioritize for improvement, whether it's the raw material extraction stage or the distribution stage, among others. This process also facilitates open discussions and the potential for reaching compromises among stakeholder preferences.

Interpretation

Lastly, the outcomes of the assessment will be presented in the most informative manner, often through visualizations and graphs. This approach ensures that the assessment leads to well-founded conclusions and recommendations aimed at mitigating the environmental impact of the forthcoming product or service. Typically, these recommendations are formulated by addressing key questions, such as whether the manufacturing stage excessively consumes resources like energy, or if the energy expended during production will be offset by usage efficiency. This information, in turn, equips relevant authorities with the insights needed to make informed decisions and implement suitable actions, potentially leading to reductions in both financial costs and environmental impacts.

LCA CASE STUDIES

General Application

An example of general application of LCA studies for product or services is by a company in Switzerland that assessed LCA on a lungo cup of coffee made from *Nespresso* Original capsule. Comparison was made in this assessment with other coffee systems found in Switzerland, which include: Moka, a drip filter and a full-automat system. Coffee is one of the important industrial beverage products. *Nespresso* revolutionised coffee culture with its invention of a compact portioned coffee system for easy at-home use. However, questions began to arise with regards to the use of portioned coffee capsules will lead to environmental impact due to the use of resources in the production process and the impacts of the capsule packaging after usage. Therefore, in 2018, *Nespresso* commissioned Quantis, a leading consulting firm specialised in sustainability, to perform a life-cycle assessment (LCA) of a cup of lungo coffee(100ml) made from various coffee systems, at home, in Switzerland.

1. Goal definition & scoping

The study was designed with the primary objective of addressing two key questions:

1. What is the impact of the *Nespresso* preparation system on the environment?
2. How does it compare to other coffee preparation systems commonly used in Switzerland?

This study assessed the life-cycle of a lungo cup of coffee(100 ml) from the extraction and processing of all raw materials through the end-of-life of all components, including packaging (a cradle-to-grave approach) and the impact of a lungo cup of coffee prepared using the *Nespresso* Original system in Switzerland compared with three other coffee preparation systems commonly found in the Swiss market: a Moka, a drip filter and a full-automat system.

2. Inventory analysis

To determine the environmental impact of the *Nespresso* preparation system, fully automatic machines, Moka and filter coffee, the study considered the following stages of the coffee product life-cycle.

1. Green coffee supply
2. Packaging product & delivery
3. Manufacturing
4. Distribution
5. Use
6. Overheads / support
7. End - of - life

In the initial phase of the study, a comprehensive analysis is conducted, encompassing the entire coffee cultivation process. This includes an assessment of agrochemical usage, irrigation practices, land use alterations, as well as the energy and water consumption involved in the processing of coffee cherries into green beans destined for European markets. Subsequently, in the subsequent phase, the study delves into the environmental impact associated with the materials used in coffee packaging and capsules. This examination encompasses various levels of packaging, including primary packaging, exemplified by elements like aluminium capsules for brands such as *Nespresso*, secondary packaging such as sleeves, and tertiary packaging employed in transportation, such as Euro Pallets and large cardboard boxes.

The evaluation of the manufacturing phase encompasses all aspects of further coffee processing, including roasting and grinding at production sites, such as Avenches for *Nespresso*. This manufacturing process is consistent across all coffee systems under examination. Roasting and grinding are carried out using drip filters and Moka pots, whereas *Nespresso* and fully automatic machines employ coffee beans. It’s worth noting that the energy consumption associated with bean grinding is minimal. Distribution encompasses the transportation routes from production facilities to the point of sale or directly to customers. In the case of *Nespresso*, distribution channels include boutiques, supermarkets, involving consumer shopping trips, or postal delivery.

The study meticulously assesses various facets of the use phase’s environmental impact. In addition to the energy and water utilized in coffee brewing, it also scrutinizes the complete life-cycle of machines, encompassing their production, materials, delivery, maintenance, and disposal. Furthermore, the study examines cup production and washing processes.

The overheads/support phase investigates elements related to the company’s infrastructure, such as the *Nespresso* headquarters in Lausanne and Swiss call centres. While data for this phase is available only for Nespresso, it is presumed that similar life-cycle stages exist for the other coffee systems. Consequently, the same impacts per cup of coffee related to overheads/support are considered across all coffee systems.

The final stage, pertaining to the end-of-life of the product, encompasses activities like collection, sorting, and recycling of packaging materials, capsules, and coffee grounds. For *Nespresso*, the end-of-life approach entails a 50% recycling rate and 50% incineration with energy recovery, mirroring the situation in Switzerland.

3. Impact analysis

The use stage has the greatest environmental impact on all examined coffee preparation systems. The cup production and washing have the largest contribution to the use stage carbon footprint (38-62%), except for the full automat coffee system where impacts are dominated by the machine production due to its heavy weight (40%). The impact caused during brewing typically represents about 17-33%. For drip filters, the paper filter production and distribution were also included, representing 8% of the drip filter using stage carbon footprint.

The cultivation of coffee has the second greatest influence on greenhouse gas emissions. All coffee systems were examined using the same Green Coffee Supply and Deforestation Model for better comparability across systems despite a lack of comparative data from other companies (full automat, drip filter, and Moka can use a wide variety of coffee in terms of origin, farming practices, and cherries treatment). The differences observed among the systems are related to the amount of coffee used per cup only.

Next is the packing and delivery impact. The coffee pouches (a laminate of plastic and aluminium) used for the other systems are assumed to be the same for all, but the amount of coffee per cup varies. The impact of the *Nespresso* coffee system in the packaging stage is higher than for the other three coffee systems (3.5 to 5 times higher). This is mainly due to the amount of aluminium that is needed to produce the capsules, i.e., the primary packaging. This distribution stage emits about 2 g $CO_{2\text{-eq}}$ for all coffee systems and is driven at 70% by retail and boutique activities. The remaining distribution emissions are almost entirely driven by the transport activities – postal delivery or transport to the retail and boutiques.

The manufacturing impacts are calculated per kg of coffee, and therefore the systems have a higher or lower manufacturing impact depending on the amount of coffee used per serving. With regards to overheads/support, no evidence could be found on how a specific coffee system could perform better than another; therefore, no differentiation could be made based on this stage.

The end-of-life of the different coffee systems lead to net greenhouse gas emission benefits ranging from -5 g $CO_{2\text{-eq}}$ (Nespresso) to -1 g $CO_{2\text{-eq}}$ (Full automat). This general greenhouse gas emission benefit is mostly explained by the end-of-life of coffee grounds which leads to negative emissions for all coffee systems (the different treatments include incineration with energy recovery, composting, or biogas generation). The machine end-of-life represents less than 3% of the machine production impacts.

4. Interpretation

Comparisons of *Nespresso* preparation system with other systems - the drip filter coffee system, the Moka coffee system, and the Full Automat coffee system are shown below.

Nespresso with the drip filter coffee system:

- The use stage impact of the drip filter is slightly higher than the *Nespresso* coffee system due to the one-way filter paper and the higher energy consumption during coffee brewing.
- The green coffee supply stage for the drip filter coffee system is slightly more impactful because the assumed amount of coffee for 110 ml is 6.4 g as compared to 6.1 g of a Nespresso capsule.
- The drip filter coffee system is subject to high consumer-related variations.

Nespresso with the Moka coffee system:

- The Moka and the *Nespresso* coffee systems have similar environmental impacts.

- The use stage impact of the Moka coffee system is similar to *Nespresso*. The higher energy consumption of the Moka coffee system during coffee brewing is evened out with a less impacting machine production, distribution and cleaning.
- The green coffee supply stage for the Moka coffee system is more impactful because the assumed amount of coffee is 8.5 g compared to 6.1 g of a *Nespresso* capsule. It has to be kept in mind that the cup of coffee made from the Moka coffee system is slightly smaller than the one prepared by the other systems (100 ml instead of 110 ml) due to the inherent size of the Moka coffee maker.
- The Moka coffee system is subject to high consumer-related variation.

Nespresso with the full automat coffee system:

- The full automat coffee system appears to be the coffee system with the highest environmental impacts.
- It has a 30% higher carbon footprint than the *Nespresso* coffee system.
- The most significant impacts associated with the full automat coffee system are driven by 2 parameters: the large amount of coffee used per cup – with 9 g per cup, the full automat uses a considerably higher amount of coffee than the *Nespresso* preparation system (6.1 g) - and the heavier machine (9.1 kg vs. 2.4 kg) which contributes heavily to the impacts associated with the machine production and distribution. The two machines are assumed to have the same lifetime and usage intensity (i.e., 2 cups/day, which is the average home consumption in Switzerland). More intensive use of the machine would reduce the contribution of the machine production to the overall carbon footprint and the difference between the two scenarios.

In conclusion, a holistic view of the life-cycle of the four different coffee preparation systems shows that drinking a 110 ml lungo cup of coffee made from a Nespresso coffee system in Switzerland has a similar environmental impact as the same cup of coffee made with a drip filter coffee system or a Moka coffee system. On the other hand, preparing a cup of coffee with a full automat preparation system has a higher environmental impact since the machines are heavier and a greater amount of coffee is used.

The environmental impact of coffee consumption experiences a notable escalation due to consumer behaviours, particularly instances where consumers fail to measure coffee precisely, discard leftover coffee, or employ coffee machines in an inefficient manner. This impact, particularly concerning energy consumption, is significantly influenced by consumer behaviour, with unportioned coffee systems being more sensitive to it compared to portioned coffee systems. In simpler terms, a consumer can achieve a lower environmental impact when using a drip filter or Moka coffee system under certain conditions, as opposed to preparing a higher-impact cup of coffee with these systems compared to the Nespresso Original coffee system. Consequently, the Nespresso coffee system emerges as a dependable and consistent solution in mitigating environmentally irresponsible coffee consumption practices

Benefits of capsule coffee systems includes:

- *Precise use of resources:* The *Nespresso* system uses the exact amount of coffee, energy and water needed for each cup of coffee, so no unnecessary resources are wasted during preparation.
- *Less risk of food waste:* The single-portioned coffee system ensures that only as much coffee is prepared as it is actually consumed – hence no coffee grounds are wasted, and no unused portions are thrown out.
- *High energy efficiency: Nespresso* machines need little time to be heated and are equipped with an automatic switch-off/standby function to reduce energy consumption.
- *Built-in usage consistency:* The performance of the Nespresso system eliminates the variations of consumer behaviour with aspects such as an automatic on/off switch and design to brew the exact amount of coffee in each capsule.
- *Recycling:* The environmental balance is improved if the aluminium capsules are collected and returned to the Nespresso recycling system.

Limitations that were found during the LCA were:

- The *Nespresso* coffee system is modelled with more details and granularity because primary data were available for this model. As one of the purposes of the study was to better understand the impacts of the *Nespresso* coffee system, it was decided to keep all available data on this system, even if it was impossible to find detailed data for the comparative systems.
- This study focuses on the Swiss market, and the results observed are therefore true only for this specific market.
- The green coffee cultivation is assessed following the Product Environmental Footprint Category Rule (PEFCR) for coffee, and the same coffee is applied for all systems. If one of the systems is sourcing from completely different origin or farms with completely different practices, this could lead to differences in production, less or more land use change impacts, or lower or higher delivery distances.
- Biogenic CO_2 uptake and release from the coffee; which pertains to the CO_2 absorbed by the coffee plant during its growth and subsequently released when coffee grounds decompose or are subjected to incinerationhas not been included. Nonetheless, it is acknowledged that nearly all the coffee waste will be effectively degraded at the end of its life-cycle through composting, mechanization, or incineration. Consequently, the overall carbon balance remains neutral for these end-of-life disposal methods. It is essential to note that landfilling is not a viable option for municipal waste in Switzerland, and therefore, it was not included as a consideration in this study.

ENVIRONMENTAL APPLICATIONS

This example depicts how this assessment method was used to analyse the environmental impacts of urban parks in South Korea.

Goal definition & scoping

The goal of this assessment was to analyse the carbon emission and uptake of the typical South Korean urban park over its lifespan which was about 30 years.

The scope focused on:

- Production of agricultural materials, vegetation, and paving materials.
- Transport.
- Construction, as grading, planting and pavement.
- Vegetation growth and management.
- Demolition - focusing on the removal of trees & paving materials, and loading the waste in the truck.
- Disposal - concentration on transport to the waste disposal facility towards landfilling or incineration.

Inventory analysis

Diesel consumption per square metre for the preparation and management of the soil and plants was calculated. Then the energy consumption for production of paving materials and carbon emission was calculated.

For transportation, the carbon materials were calculated using how much energy was consumed for the typical one-way transport factoring several factors such as individual material, truck fuel efficiency and loading capacity.

Several factors that were taken into consideration when calculating the carbon emissions for construction;such as the type of construction and relevant work involved, the equipment and material input, as well as the working hours and fuel efficiency of the equipment, that affected the energy consumption, thus affecting the carbon emission.

Vegetation growth was used to calculate the carbon uptake that can be sequestered by the above ground biomass. The species, size, density of the trees, the basis of the field survey, design details and drawings of each park were used to calculate the carbon uptake.

Management activities such as irrigation, fertilisation, pruning, application of pesticides had also contributed to carbon emissions. A survey inventory was determined after interviews with officials in charge, acquisition of maintenance statements and other actual measurements. The study examined the materials and types of equipment input, frequency, amount and energy consumption in each process of the management activity. Since guidelines and sidewalk management in Korea recommend replacing paving materials after at least 10 years, paving management only includes energy consumption according to the repainting of the deck, excluding those parts to be reinstalled.

Carbon emissions for demolition and disposal were estimated using a few assumptions due to the variations like remodelling of a park after construction, as well as the difference in what has been disposed of from alterations. It was assumed that all paving materials were demolished, 20% of trees were removed, it took 20km to reach the transport facility, and trees were incinerated while paving materials were landfilled. Energy consumption and waste were also calculated based on the estimation standard of landscape architecture.

Impact analysis

The total carbon emission was calculated by the formula, C = CU - CE, where C is the carbon budget, CU is the cumulative carbon uptake of vegetationand CE refers to the carbon emissions from the material life-cycle.

CU is determined by the equation:

$$CU = \sum_{i=1}^{n} GU_i + \sum_{i=1}^{n} TU_i$$

Where, *GU* is the annual carbon uptake of grass while *TU* represents the total uptake of carbon sequestered annually by trees as they grow. $TU = (D \times T) \times Q$, where *D* is the annual stem diameter growth rate of trees; *T* is the age of trees and *Q* is the carbon uptake quantitative model of tree species.

CE is determined by $CE_{direct} + CE_{indirect}$,

Where direct sources of carbon emission are fuel sources, like gasoline, diesel and electricity and indirect sources were determined by products and actions like fertiliser, compost, pesticide, fungicide, herbicide, oil stain and irrigation.

Interpretation

In this section, there were additional results that showed that out of the three main cover types, grass had the largest makeup, followed by pavements and trees and shrubs. Additionally, bricks, ochre & sand, followed by concrete were the top three types of pavements out of the seven pavement land cover types. It was also found that Canadian (Toronto) parks had paved area (grass, bricks and concrete) of 10% out of the total park, but the paved area percentage is 30% in South Korean parks.

It was found that the carbon budget can be successfully balanced, with the potential to achieve net-zero carbon emissions within 20 years of construction. This would ultimately lead to the park having a carbon-negative footprint once it reaches its 30th year post-construction.

The final conclusions drawn from the analysis, based on ecological design and construction strategies, are as follows:

- The capacity for carbon uptake (CU) is dependent on factors like land use type, landscape materials, and tree planting arrangements.
- Grass and impervious surfaces emerge as key contributors to carbon emissions (CE).
- The predominant land cover type, specifically brick and concrete, exhibits significantly higher carbon emissions, up to 10 to 15 times more than other materials, consequently reducing CU capacity.
- Carbon uptake (CU) varies depending on tree species, planting density, size, and vertical structure, even when the planting area remains consistent.
- The primary contributors to carbon emissions (CE) during the construction phase are associated with vegetation irrigation and alterations to natural topography.

Based on the nine provided recommendations, we can summarize them into three overarching guidelines:

- Promote a design approach that incorporates multiple layers of trees while minimizing the use of grass and pavements, which can enhance carbon uptake and reduce emissions.
- Encourage the recycling and upcycling of materials that are removed during construction, such as old trees and pavement materials,

for reuse in other park projects or alternative applications.

- Implement the transformation of impervious areas into previous ones, converting empty paved spaces into green patches, as a strategy to mitigate carbon emissions and enhance ecological sustainability.

ADVANTAGE, DISADVANTAGE AND LIMITATIONS OF LCA

The examples provided above clearly demonstrate the versatile applicability of Life-Cycle Assessment (LCA) across a wide array of products, services, and environmental studies. LCA emerges as a powerful tool capable of significantly advancing environmental research by aiding in the identification of potential, unforeseen consequences associated with proposed solutions, which might inadvertently shift the environmental problem elsewhere. Its utility extends to offering a comprehensive and systematic approach to research while placing the outcomes of environmental policy and design decisions into a meaningful context (Miller 2022). Furthermore, LCA can serve as a fundamental conceptual assessment tool for gaining a deeper understanding of its environmental impact. However, despite its versatility, the effectiveness of LCA is contingent upon the availability of data to enhance precision when conducting official reporting. This assessment method can be effectively complemented by other assessment approaches, such as cost-benefit analysis (CBA), to yield more economically viable and favourable outcomes.

Consequently, our interpretation leads us to conclude that LCA holds substantial promise for advancing future environmental research. One of the key implications of this study is the potential for fostering increased environmental research utilizing the LCA methodology. This, in turn, could pave the way for the development of projects that are both environmentally friendly and have a low impact on the environment. Nonetheless, it is important to acknowledge the limitations of this study. One notable limitation is the focus on specific examples of how LCA can be applied in environmental research, which may have somewhat restricted the overall comprehensiveness of this paper.

Hence, we aim to provide recommendations to be taken into account when employing this assessment method for future projects of a similar nature. The following are some key considerations to keep in mind when conducting an LCA:

- *Consider the scope of your LCA carefully:* Determine whether you need a comprehensive or summarized LCA, depending on the specific goals and requirements of your project.
- *Seek professional expertise:* Engage experienced professionals, including auditors from reputable auditing firms and relevant department representatives, to provide guidance, ensure accuracy, and offer valuable recommendations throughout the LCA process. Expert assistance can be sought through platforms such as AGV Sustainability or One Click LCA.
- *Proceed systematically:* Given the potential complexity, especially in the case of detailed LCAs, it is advisable to approach the assessment step by step or inventory by inventory. This approach minimizes stress, reduces inaccuracies, and mitigates complications that may arise during the process.
- *Collect your own data:* Whenever possible, gather and measure your own data instead of relying solely on external sources. Data availability from external sources can be limited and may not align perfectly with the specifics of your study, so obtaining your measurements ensures the data's relevance and accuracy.

These recommendations will help to make the assessment more accurate and reliable.

The overview of LCA is that it analyses the material used and released in each stage of the product or service's life-cycle, which helps us to analyse the relevant environmental impacts. Through that, we can derive recommendations, benefits and limitations of the products or services. However, in the case where data is limited, interpretations are made to support the points.

Despite these advantages, LCA has several limitations such as the lack of equipment or data, leading us to apply interpretation without any evidence to support them. LCA is a 'site independent' method than a 'site specific' assessment method. Though, LCA can offer a variety of benefits when evaluating

Table 3: Advantage and disadvantages of LCA (adapted from Gregory *et al.* 2009)

Advantage	Disadvantage
• Detailed and flexible • Provides a comprehensive overview of environmental impacts including scarcity and toxicity. • Uses readily available data which is frequently updated. • LCA can guide a company's decision-making process (micro-economic level) and help governments define a public policy (macro-economic level)	• Expensive, data intensive and time consuming • Requires value judgement on environmental priorities. • Requires extensive detailed knowledge to conduct and interpret. • Data availability and accuracy. The accuracy of a LCA study depends on the quality and the availability of the relevant data, and if these data are not accurate enough, the accuracy of the study is limited. These facts affect the precision of the results. • Does not directly incorporate environmental data. • Policies do not influence all material metrics evenly.

the environmental impact of the products/services, but the methodology calculates global and regional environmental effects than local effects. On the other hand, performing an LCA study is resource-consuming as the assessment requires large amount of data. Poor data collection, or absence of reliable data will not lead to solid conclusions or the evaluates non-real environmental impacts (Muthu 2020). Nevertheless, LCA can quantify the impacts of individual materials during environmental studies and help provide a framework to discuss those trade-offs (Miller 2022). However, this assessment method is not perfect, and there are some drawbacks when we have limitations, such as the lack of equipment or data, leading us to apply interpretation without any evidence to support them. The table below lists the pros and cons of this assessment method.

CONCLUSION

Our research has revealed the existence of numerous simulation tools designed for conducting LCA. These tools facilitate the visualization of fieldwork projects through software and applications, enabling the evaluation of environmental impacts and informed decision-making without the need for physical experiments. This approach proves advantageous as it offers a cost-effective means of gaining a comprehensive overview of fieldwork endeavours. Prominent examples of these simulation tools include SimaPro, One Click LCA, Gabi, Umberto LCA, and openLCA, with SimaPro, GaBi, and Umberto being among the most widely used.

Conducting an LCA involves a collaborative effort, necessitating the involvement of various individuals with diverse expertise. The LCA team comprises professionals ranging from consultants with specialized knowledge in LCA processes to organizational staff responsible for different facets of the product or service under analysis. Key roles in this process include:

- Environmental expert: The primary project manager and technical resource overseeing the LCA project.
- Engineer: An expert in engineering management systems who provides access to engineering data and expertise.
- Manufacturing/Operations: Individuals who furnish operational information crucial to the assessment.

In addition to discussing the process of LCA, we have also drawn distinctions between LCA and another assessment methodology, CBA. Two fundamental differences were identified:

Firstly, LCA scrutinizes the use and release of environmental resources at each stage of a product's life-cycle, whereas CBA encompasses a broader spectrum, encompassing environmental and non-environmental inputs, including financial costs and manual labour. From these inputs, both tangible (quantifiable) and intangible (unquantifiable) costs and benefits are calculated to ascertain whether the benefits outweigh the costs, determining whether the practices lead to a profit or loss. Secondly, while LCA primarily focuses on minimizing the environmental impact of a product or service, CBA emphasizes the maximization of benefits, spanning social, economic, and environmental dimensions. Notably, CBA can be integrated into the LCA process to evaluate the economic and sustainable aspects of actions taken to mitigate environmental impacts.

In conclusion, this paper is intended to serve as a valuable resource for readers, researchers, and organizations interested in understanding and applying LCA, particularly in the context of environmental research. Its objective is to provide a clear comprehension of the core objectives, processes, and underlying principles of LCA, thereby assisting in the identification of opportunities for enhancing the sustainability of products or services. The paper is poised to aid organizations in making informed decisions for more effective and environmentally conscious projects. It serves as a stepping stone for future researchers and organizations embarking on LCA endeavours by offering theoretical insights, case studies, observations, and practical advice to guide environmental projects and research in the future.

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REFERENCES

Brusseau, M.L. 2019. Chapter 32 - Sustainable Development and Other Solutions to Pollution and Global Change. Environmental and Pollution Science (Third Edition), pp. 585-603, Academic Press. https://doi.org/10.1016/B978-0-12-814719-1.00032-X

Burnley, S., Wagland, S. and Longhurst, P. 2019. Using life-cycle assessment in environmental engineering education. *Higher Education Pedagogies*, **4**(1): 64-79.

Ciacci, L. and Passarini, F. 2020. Life-cycle Assessment (LCA) of Environmental and Energy Systems (Editorial). *Energies*, **13**: 5892.

Farjana, S.H., Mahmud, M.A.P. and Huda, N. 2021. Chapter 1 - Introduction to Life-Cycle Assessment. *In:* Life-Cycle assessment for Sustainable Mining, Elsevier, pp. 1-13. https://doi.org/10.1016/B978-0-323-85451-1.00001-9.

Golsteijn, L. 2022. Life-cycle Assessment (LCA) explained. PRé | Fact-based sustainability.

Gregory, J., Fredholm, S. and Kirchain, R. 2009. "Is economic value an effective proxy for embodied energy and environmental impact in material systems?" Sustainable Systems and Technology, 2009. ISSST '09. IEEE International Symposium on. 2009. 1-5. ©2009 Institute of Electrical and Electronics Engineers. http://dx.doi.org/10.1109/ISSST.2009.5156777

Jolliet, O., Saadé-Sbeih, M., Shaked, S., Jolliet, A. and Crettaz, P. 2016. Environmental Life-cycle Assessment, CRC Press, Taylor and Francis Group.

Miller, S.A. 2022. The capabilities and deficiencies of life-cycle assessment to address the plastic problem, pp. 01-03, 08. Frontiers in Sustainability.

Muthu, S.S. 2020. Chapter 6- Estimating the overall environmental impact of textile processing: Life-cycle assessment of textile products. *In:* Assessing the Environmental Impact of Textiles and the Clothing Supply Chain, Second Edition, Elsevier, Science Direct.https://doi.org/10.1016/B978-0-12-819783-7.00006-5.

Statistics Canada. 2013. Human Activity and the Environment: Measuring ecosystem goods and services in Canada. Environment Accounts and Statistics Division, published by authority of the Minister responsible for Statistics Canada, Catalogue no. 16-201-X, ISSN 1923-6751, December 2013.

TED-Ed. 2020. *Which bag should you use? - Luka Seamus Wright and Imogen Ellen Napper* [Video]. YouTube. https://www.youtube.com/watch?v=3_fjEc4aQVk

UN Sustainable Goals. 2016. United Nations Sustainable Development Goals, United Nations.