The Evolution of Life Cycle Assessment Approach: A Review of Past and Future Prospects

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Abstract. There is consensus evidence that the thousands of years known earth’s capability to sustain life has been seriously eroded, especially since the industrial revolution. Modern forms of human existence related to prompt economic development have given a massive share in the permanent degradation of the plant, its ecosystem, resources, and quality of life of its inhabitants. Consecutively, there is increasing environmental awareness in material use and its environmental impacts, resulting in the proliferation of environmental assessment tools such as Life Cycle Assessment approaches. Ever since the first approach was proposed in the 1960s, LCA has undergone robust development in both approaches and applications. It is now a well-known and widely used tool across the industry, academia, and policy. So, this paper aims to introduce the LCA hotspots in history with a highlight on the main five periods: Early years period, conception period, standardization period, elaboration period, concept period. It is vital to address the growth in the futuristic aspiration of the new methodology related to integrating Building Information Modelling (BIM) with the LCA procedure to provide real-time results in the early design stages.

1. Introduction
Sustainable development was developed its official definition in the Brundtland report 1987 to eliminate the negative consequences of rising only the quality of life for the present generation. It embraces the idea of having the ability to meet the current needs without threatening the future capability to satisfy their own needs [1]. Based on the fact that we are rapidly depleting non-renewable resources; energy, and raw materials, the consciousness of sustainability has rapidly increased worldwide in the last decade. The awareness is with the target of avoiding the environmental impacts occurred by different types of human activities. Activities with harmful ecological effects vary from one industry to another. However, it is stated that the building industry is the most contributor to Green House Gases emissions (GHG). [2]

The ACE sector (Architecture, Construction and Engineering) has intensive attention as the building industry robustly influences the environment. It is considered to have the largest share in the natural resources drain and the foremost reason for undesirable impacts such as air and water pollution, solid waste, deforestation, toxic wastes, health hazards, global warming, and other harmful
effects [3]. It is considered as the most leading cause of carbon emissions and energy consumption as it represents 36% of worldwide energy use and nearly 40% of total direct and indirect CO2 gas emissions [4]. Global warming currently is one of the highest profiles which is a consequence of the long-term accumulation of GHG emissions; CO2, CH4, N2O, etc., in the higher layer of the atmosphere. [5]

GHG emissions impacts have the most consideration from researchers and policymakers, although it is just one of a wide range of impacts [6]. So, it becomes clear that there is a need for a holistic perspective of materials to evaluate all the environmental impacts throughout its whole life cycle. Thus, to evaluate a material's total impacts, all life cycle stages as shown in (Fig1) must be considered, from material extraction, manufacturing, construction, use, including operations, maintenance, demolition, and disposal. [7]. The main reason for considering all types of environmental issues is to avoid what is called “Burden Shifting”. It happens when the improvement in a specific stage of the material life cycle concerning one kind of environmental impact can lead unintentionally to a rise in the other types of impacts for the same stage or different life cycle stages. [8].

![Fig 1:Life Cycle stages of a building with different approaches](image)

In that context, Life Cycle Assessment (LCA) has been indicated to be an applicable emerging approach to evaluate products and materials concerning their environmental performance. LCA has undergone a robust development in approaches and applications since it was conceived in the 1960s [9]. LCA promises to strengthen the architectural decision-making by investigating the environmental impact of buildings materials and concluding to techniques to decrease these impacts [10]. Even though the LCA method provides a quantifiable measurement of environmental impact, awareness of the strength and weaknesses points of LCA is essentially required to ensure the ability to understand the LCA procedure. [7]

From the early beginning to now, methodological development of (LCA) has still undergone with attention to the new approaches and tools to support the seamless procedure. So, this paper aims to give a comprehensive historical overview of the (LCA) development throughout the years, focusing on the scope of approaches development, application, international standardization, and broadcasting. In addition, the paper also addresses the futuristic aspiration of the new methodology related to integrating Building Information Modelling (BIM) with the (LCA) procedure.

2. Life Cycle Assessment (LCA): Philosophical perspective

The LC allegory is driven from the biology field. In biology, the “LC” term refers to the organism constant sequence of changes from one initial form, as a gamete, to the development of the same form again for the cycle to be repetitive” [11].

2.1. Philosophy of construction- economy development

The economy has adopted a linear philosophy for quite a long time. The Linear Economy concept in the construction sector as shown in (Fig 2) is based on raw material take-make-use-dispose. This concept seeks a short-term consumption of materials resources and if it remains in the linear model, the reserves available for materials will be depleted in a few decades. It has resulted in environmental issues such as climate change, natural capital loss, and health problems, etc.. [12]
Despite the linear economy success in generating material fortune in the industrial countries up to the 20th century, it has shown a weakness in the new millennium [13]. Thus, as shown in (Fig 3) Circular Economy philosophy (CE) is swept over in the construction sector which emerges as a counterpoint to the Linear one. In CE, products and raw materials are designed to be reusable to maintain and enhance natural resources and minimize risk by managing limited resources and renewable loops. [14]

According to the European Academies Science Advisory Council (EASAC), there are critiques of the CE related to the recycling process. Achieving the closed-loop of a material that already caused pollution, waste through its life cycle requires energy and resources. This consumption is used for the recovery and recycling process which increases in a nonlinear manner as the percentage of recycled material rises. [15]

Furthermore, in addition to mitigating environmental impact, companies using this concept can reduce besides the environmental impacts reduce the production cost, the dependence on natural raw materials, and also reduce the environmental. To understand the concept of CE, a philosophy of Life Cycle Thinking (LCT) has been engaged in the construction field to have a comprehensive perception of the material life cycle. [14]

2.2. The Philosophy of Life Cycle Thinking (LCT)

In a simplified way, every material has its own lifetime process called the Life Cycle. It has been proven that a material’s life cycle results in a wide range of environmental impacts. Therefore, the Life Cycle Thinking (LCT) concept refers to taking into consideration the upstream and downstream of the material in a holistic perspective. [16]

Furthermore, the LCT concept deals with all material life stages as shown in (Fig 4) from the raw materials and the energy used to manufacture the material to the packaging, distribution, use, maintenance, and finally recycling, reuse, or final disposal. Each one consumes energy, water, and resources and results in waste, emissions, and a specific environmental impact. This concept has its target to mitigate this consumption and promote material performance. [17]
Furthermore, LCT philosophy is equivalent to the "6 RE philosophy" which includes as shown in (Fig 5), a) rethink about the material or product and its functions, b) reduce the depletion of the energy and natural recourse, c) replace the material with harmful effect with the environmental option, d) recycle the material to make a closed-loop and reduce the waste, e) reuse the existed material, f) repair the material. [16]

Fig 5: The 6 RE Philosophy concerning eco-design principle. [16]

LCT is a mindful approach that goes beyond the traditional linear concept by analyzing a product or material life cycle (from the cradle to the grave) and engaging the three sustainability aspects in the approach as shown in (Fig 6). These aspects are the environmental aspect embodied in the LCA as a tool, the social aspect represented in Social Life Cycle Assessment (SLCA), and the economic aspect embodied in Life Cycle Costing (LCC). Keeping all three in balance is the key to make sustainable products or materials. [18]

Consequently, the ultimate target of LCT is to enhance the environmental and Socio-Economic performance throughout its life cycle. In detail, it aims to help companies and customers to be more aware of how their decisions impact the environment from a holistic perspective and make better alternative decisions to mitigate environmental impacts. [18]

2.3. LCA formal definition
Throughout the years, LCA has had different attempts to be officially defined as a new approach. The first initial definition was introduced in 1990 by the SETAC workgroup as a comprehensive tool for assessing the environmental burdens related to a product, process, or activity by analyzing the energy, materials used, and wastes generated. The assessment involves the product's whole life cycle from extraction of raw materials, manufacturing, transportation and distribution, use/reuse/maintenance, recycling to final disposal [19]. Furthermore, ISO 14040 also defined LCA as a systematic approach for evaluating the inputs and outputs of materials and energy related to a process or product to analyze the potential environmental impacts caused throughout its life cycle. [9]

3. Life Cycle Assessment (LCA): Historical perspective
The development of Life-Cycle approaches has been driven by concerns related to the environmental pollution and the depletion of materials and energy. Ever since the first methodology was proposed in the 1960s, LCA has undergone robust evolution in both methodology and applications. So, it is now a well-known and widely used tool across the industry, academia, and policy [8].

From its start in the 1960s to the broad-spread in just over 60 years, LCA has passed through different stages of development and adoption as shown in (Fig 7); a) the early years period (1960-1970), b) Conception period (1970-1990), c) Standardization period (1990-2000), d) Elaborations’ period (2000-2010), e) Concept broadening period (2010-till now) [20]. The major transition events in the LCA history are summarized chronologically in (Fig 8) and will be discussed in detail in the below sections. [20]
Fig 7: Life Cycle Assessment (LCA) development over 60 years

Fig 8: The timeline of the transition events in LCA history
3.1. The early years period (1960-1970)
LCA had its initial steps in the 1960s as shown in (Fig 9) in finding ways to take into account the energy and materials' resources throughout the product manufacturing. Various of these early LCA attempts weren't published as they were either commercially sensitive or internal company reports never planned for public distribution. The Coca-Cola Company was the first manufacturing firm to address LCA related to its beverage containers. As in 1969, the company funded research to evaluate the consumption of material resources and the environmental impacts. [21]

![Fig 9: The transition events in the early period (1960-1970)](image)

3.2. The conception period (1970-1990)
The period 1970-1990 embodied the LCA conception spread with broadly diverging approaches, terminologies, and results. During the 1970s and 1980s, LCAs were carried out utilizing various methodologies without a common theoretical framework, as illustrated in (Fig 10). Firms used LCA to satisfy the substantiate market demands. In 1974, U.S Environmental Protection Agency (US. EPA) performed the first peer-reviewed study to inform regulation on the packaging. The results varied considerably for the same product, prohibiting LCA from becoming a more widely recognized and used analytical method. [22]

![Fig 10: The transition events in the 1970s period.](image)
Alongside these specific events, there are two transition events in the LCA development through the 1970s. The process of predicting environmental burdens and material resources used is known as a Resource and Environmental Profile Analysis (REPA) in the U.S and Eco-balance in Europe. Between 1970 and 1975, approximately 15 REPAs were performed. Within this time, protocol or methodology for conducting these studies was developed, including several assumptions. During these years, EPA and major industry representatives had considerably reviewed these assumptions and techniques. [8]

From 1975 to the early 1980s, the European Commission established the Environment Directorate (DG X1) to develop methodologies similar to those used in the United States, which piqued European interest. In addition to standardizing pollution regulations in Europe, in 1985, (DG X1) published the Liquid Food Container Directive to examine the energy and raw materials consumption and the solid waste creation of liquid food containers. [8]

During the 1980s, a wide range of consultants and researchers as shown in (Fig11) has been developed the methodology. The need for dedicated LCA software has been identified as a result of the demand to go beyond the inventory to impact assessment. Around 1990, the first version of SimaPro and GaBi, two extensively used programs, were announced. Until the 1990s, LCT wasn’t a well-known concept outside of the packing industry. [23]

**1988: Broad Base of Consultants and Researchers**

- The approach has been refined and expanded by a wide range of researchers and consultants from all around the world. LCA methodology has gone to a new level of development due to the necessity to overtake the inventory to impact assessment.

**1989: MS&E Report**

- The “materials tetrahedron” concept was the work base in the *The Materials Science and Engineering (MS&E)* report that focused mainly on the using of materials.

**1989: GaBi Software**

- *GaBi Software*, the most common program was released in 1989. It was one of the primary commercial software tools to take part into the market-leading LCA tool and data base.

**1990: SimaPro Software**

- *SimaPro*, another widely used commercial LCA software, was released in its first version

**1990: Life Cycle Thinking Concept**

- The International Chamber of Commerce and the Society of Environmental Toxicology and Chemistry (SETAC) organized conferences and working groups to improve and standardized LCA methodology. *Life Cycle Thinking (LCT)* was Until the 1990s, LCT wasn’t a well-known concept outside of the packing industry.

**Fig11:** The transition events in the 1980s period. [23]
3.3. The standardization period (1990-2000)

The number of seminars, guides, and handbooks in the 1990s reflected the outstanding global coordination activities growth. From 1991 to 1994, a cooperation amongst LCA specialists was established through the North American and European branches of the Society of Environmental Toxicology and Chemistry (SETAC). This collaboration was resulted continual development and standardization of LCA framework and methodology. One of the most important outcomes of this coloration was the “Code of Practice”. [5]

Moreover, the International Organization for Standardization (ISO) has been engaged in LCA since 1994. Parallel to the focus of the SETAC working group on improving and harmonizing methodologies, ISO took the formal mission of methods and procedures standardization. Despite the lack of standardized methods, the standard met industry requirements for using LCA for product development. Over the next seven years, four standards were released based on the standard development: a) the principles and framework (ISO 14040) in 1997, b) the goal and scope definition (ISO 14041) in 1998, c) the life cycle impact assessment (ISO 14042) in 2000 and d) the life cycle interpretation (ISO 14043) in 2000. [5]

Besides these two pivotal events, there were several attempts to standardize the LCA methodology as shown in (Fig 12). For instance, the CML92 method created by the University of Leiden in the Netherlands, and the Eco-indicator method, the first endpoint assessment technique and still the furthermore widely used in LCA. [23]
3.4. The elaboration period (2000-2010)
From the beginning of the 21st century, the focus on LCA has been rapidly growing. As a result of its qualitative approach to framework, impact assessment, and data quality, it has become a vital decision support tool and broadly used methodology. So, the period 2000-2010, as shown in (Fig 13) can be defined as the decade of elaboration. This period has a broad experience in establishing recognized databases encompassing all industrial sectors and aiming for reliable standards, such as the well-known Ecoinvent Database in 2003. [22]

In 2002, the Life Cycle Initiative, international cooperation, was established by the United Nations Environment Program (UNEP) and (SETAC). It has three programs: a) the Life Cycle Management (LCM) program to raise consciousness and enhances decision-making skills by providing information; b) the Life Cycle Inventory (LCI) program with the aim of improving global access to transparent, high-quality life cycle data; and c) the Life Cycle Impact Assessment (LCIA) program to improves the quality and global reach of life cycle indicators. [22]

- **2002: UNEP/SETAC**
  - the Life Cycle Initiative, an international cooperation, was established by the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC). The Initiative has three programs: a) the Life Cycle Management (LCM) program; b) the Life Cycle Inventory (LCI) program; and c) the Life Cycle Impact Assessment (LCIA) program.

- **2003: Ecoinvent Database**
  - The resource usage and emissions of a same industrial process might varied significantly amongst databases due to variances in data standards and quality. In 2003, the first Ecoinvent database (version 1.01) was released, spanning all industrial sectors and striving for standardized data standards and quality.

- **2006: ISO 14044 Standard**
  - The ISO 14044 standard detailed the criteria and guidelines in a 2006 modification, without modifying any of the standards' requirements. The ISO 14040 series of Environmental Management standards deals with LCA methodology, but there are also standards and technical guidance reports on LCA applications such as eco-design (ISO 14062, ISO 14006), environmental performance communication (ISO 14020 series on ecotags and ISO 14063), and greenhouse gas reporting and reduction (ISO 14064).

- **2010: ILCD Handbook**
  - The International Life Cycle Data System (ILCD) was developed by The European Commission includes a database of life cycle inventory data as well as a set of methodology guidelines. The ILCD project also included a comparison of all known LCIA methodologies, comparing their approaches to evaluating the various midpoint and endpoint impact categories and determining a recommended practice for each impact category.

![Fig 13](image)

3.5. The concept broadening period (2010-till now)
Lately, in the twenty-first century, A life cycle sustainability assessment (LCSA) framework has emerged with a target of considering the environmental, social, and economic dimensions of sustainability. LCA concept was originally intended to solely address the ecological component. In contrast, as a result of these recent developments, LCA has evolved from a purely environmental LCA to a further holistic LCSA evaluation. The following is a formal LCSA framework: [24]

\[
LCSA = LCA + LCC + S-LCA;
\]
The International Society for Industrial Ecology (ISIE) established a section in 2011 to concentrate on the LCA as it was and on LCSA as a developed framework. Until the end of 2018, there are 258 papers available including 146 case study papers. The number of publications has increased as shown in (Fig 14) between 2016 and 2018 compared to before 2016. Although, a wide range of obstacles related to LCSA remains ambiguous, e.g., defining sustainability aspects and the need for multi-criteria decision analysis. [25]

Since 2012, there have been extensively ambitious opportunities to make use of the emerging digitization in the ACE sector to overcome the environmental challenges with Building Information Modelling (BIM) adoption. It enables the comprehensive exchange of building information among various experts. [26]. So, integrating the BIM method into the LCA calculation can provide instant indicators of the effects of the design decisions on the building's environmental efficiency. From the architect's perspective, this can boost the decision-making in the early design stage and improve the efficiency, time-consuming, and complexity and hence participate in broader dissemination of the LCA implementation. [27]

Substantial evolution was observed concerning evolving BIM-LCA studies to improve the LC of buildings throughout the different design stages. As shown in (Fig 15), compared with the initial studies in 2012 and the studies and applications reached in 2015, the BIM-LCA has progressively turned from performing LCA in the early design stage to assessing the LCA based on a comprehensive design that reducing manual activities and time. [28]
Concerning achieving the acceptable level of interoperability, there is rapid development in the integration criteria between the software. The initial attempts were in 2013 using the manual integration approach where the data are transferred by copying and pasting from excel to LCA software [29]. Then in 2014, a substantial trial to achieve a more seamless integration was began with developing the first LCA plug-in for the BIM tools. In 2018, a semi-automated approach was introduced to decrease manual data entries while the data are substituted and filled automatically and the user interaction is needed for the exports and imports. Finally, in 2020, a futuristic aspiration of new methodology; automated BIM-LCA integration, was launched where the data exchange is fully automatic. This futuristic aspiration is a promising approach for architects to have real-time monitoring and to provide instant feedback on the most essential impacts for design decisions. [30]

4. Conclusion
In order to figure out the past and future prospects, a comprehensive review was done. LCA is a recent discipline with 50 years of history and less than 30 years of intensive evolution in methodologies and applications. Nevertheless, throughout displaying the hotspot of LCA development in history focusing on the main five periods, there are massive efforts from all specialists in the field, policymakers, private sectors, and firms to develop the approaches, applications, international standardization, and broadcasting. To this day, LCA methodological development has continued to overcome the weak spot and guarantee that LCA will be the most widespread comprehensive tool for environmental evaluation.

It has become commonplace that the LCA traditional approach is a complicated process with a high potential of user mistakes owing to manual data extraction that must be handled and mapped. So, BIM-LCA integration is an innovative, promising methodology that introduces new prospects for especially architects and automates data extraction between the BIM and LCA software. Although, there are still various limitations of achieving the BIM-LCA interoperability which is the recent interest for all LCA specialists.

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