State-of-the-art analysis of ESG and LCA and optimisation of ESG reporting

Jannik Bachofer
Faculty of Informatics
Technical University of Applied Sciences Augsburg
86161 Augsburg, Germany
E-Mail: jannik.bachofer@tha.de

Philipp Rabe
Faculty of Informatics
Technical University of Applied Sciences Augsburg
86161 Augsburg, Germany
E-Mail: philipp.rabe@tha.de

Philip Stolarczyk
Faculty of Informatics
Technical University of Applied Sciences Augsburg
86161 Augsburg, Germany
E-Mail: philip.stolarczyk@tha.de

Content

Abstract

Environmental, Social, and Governance (ESG) reporting has gained increasing relevance as stakeholders demand greater transparency and accountability in corporate sustainability efforts. This report includes a State-of-the-art chapter that examines the concepts of LCA and ESG, as well as their current combinations. However, this literature investigation revealed that ESG reports do not currently require uniform data, making them incomparable.

The study aims to assess the current state of ESG and LCA practices and identify ways to improve informed and reliable ESG reports.

This report extends already existing practices to create an automated and optimised ESG report by utilising smart sensors, blockchain and AI-enhanced LCA software. This work proposes a solution to make ESG reports uniform and comparable.

Introduction

Between 2011 and 2020 the disclosure of S&P 500 Index Companies publishing a sustainability report has risen from 20% to 90%. Thus, Environmental, Social, and Governance (ESG) reportings have gained significant attention as companies face increasing pressure from stakeholders to disclose their sustainability performance. Hence, this report explores the current state regarding LCA and ESG and investigates the potential for a more efficient, transparent, and reliable ESG reporting system.

This work therefore undertakes research to clarify the following questions: "What is the current state of LCA, ESG and their combination?" and "Are there opportunities for improvement to increase the quality of an ESG report?".

In the context of this study, the geographical scope is limited to the European region.

Firstly, the work addresses the state-of-the-art of LCA and ESG, examining their definitions, their combination, and key challenges. Furthermore, current standards of ESG data are explored. The final section discusses an optimised approach of a more efficient and trustworthy ESG report with advanced technologies and provides an alternative outlook.

1. State of the Art

The opening chapter provides a state-of-the-art overview, beginning with an examination of Life Cycle Assessments and Environmental, Social and Governance reporting, as well as their current combination. Additionally, this chapter addresses the standardisation of ESG data.

1.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology for evaluating, qualitatively and quantitatively, the potential environmental impacts and resources used throughout the life cycle of a product [1]. The evaluation considers five steps: raw material extraction, manufacturing and processing, transport, usage, disposal and recycling [2].

The LCA methodology is based on the requirements of the International Standards Organisation (ISO) 14040 and ISO 14044 and are currently in use. ISO 14040 describes the principles and framework for LCA, while ISO 14044 defines the requirements and guidelines for LCA studies [3]. These standards were introduced to ensure consistency, transparency, and comparability in LCA results [4].

LCA covers a broad range of environmental concerns, typically around 15. Some of them are climate change, freshwater use, land occupation and transformation, and toxic impacts on human health [4]. The core reason for considering multiple environmental categories is to avoid burden shifting [4]. Burden shifting (Scope 3 emissions) is the process of shifting ecological impacts from one stage of the production chain to another without achieving an overall reduction of emissions [4].

A Life Cycle Assessment consists of four distinct phases as shown in Table 1:

Table 1 LCA Phases and description [1, 4]

Phase	Name	Description
1	Goal and scope definition	- Determination of scope and definition of the purpose of LCA - Definition of product life cycle boundary (e.g. Cradle-to-Grave or Cradle-to-Gate) and level of detail
2	Life cycle inventory (LCI)	- Data collection (environmental inputs/outputs)
3	Life cycle impact assessment (LCIA)	- Process and calculation of data - Translation into environmental impacts
4	Interpretation Phase	- Analysis and interpretation of results - Provision of comprehensive overview

The first phase is the fundament of a LCA, it determines the scope and detail of the LCA.

The second phase LCI (Table 1) is considered as the most difficult one regarding the complexity of data collection [4]. This includes collecting data inputs e.g. raw materials, energy consumption, or water use, and data outputs e.g. emissions, waste, or by-products. The difficulty lies in collecting qualitative and quantitative data for the assessment [4].

The third phase (Table 1) calculates and processes the collected data, in this phase, the software translates the data into environmental impact.

Phase four (Table 1) provides a comprehensive overview of a product, establishing a foundation for a discussion of the study's conclusion. For instance, one objective could be to identify the production step which generates the highest emissions.

The following paragraph describes strengths and weaknesses form LCA based on the work of based on Hauschild et al. [4]. As Hauschild stated, one of the main strengths of LCA is its comprehensiveness in terms of its life cycle perspective and coverage of environmental issues. This strength facilitates the comparison of the environmental impacts of product systems, which are comprised of hundreds of processes, accounting for thousands of resources uses and emissions that occur in different locations and at different times. However, at the same time, this strength can be interpreted as a limitation, as it requests simplifications and generalizations in the modelling of the product life cycle and the collected environmental data. Considering that uncertainties in mapping resource usage and emission models are used for LCA, it would be more accurate to say that LCA calculates environmental impact potentials, rather than the factual impact. Furthermore, LCA follows the "best estimate" principle, which provides objective comparisons, because the same level of anticipation is applied throughout the impact assessment modelling. However, a limitation associated with the "best estimate" principle in LCA models is that they are based on ordinary performances of the processes and do not consider infrequent but highly problematic environmental events like marine oil spills or accidents at industrial sites. Consequently, nuclear power seems to be a relatively environmentally sustainable energy source, due to the fact that LCA models do not consider catastrophic disasters like Chernobyl or Fukushima. Since these events are extremely unlikely, it is not reasonable to include them in the calculations. These events would have a huge negative impact on LCA results. The final limitation to be addressed is that an LCA can only calculate and compare different product lifecycles and their environmental impacts to determine which product lifecycle is less harmful for the environment. What information an LCA cannot provide is, if "less harmful" is "good enough". Hence, it would be wrong to conclude that a product lifecycle is environmentally sustainable in absolute terms, regarding an LCA result, which states that it has lower environmental impact than another product lifecycle. Any pollution or use of resources has impacts on the environment, no matter how insignificant it may seem.

From these stated limitations, it is possible to identify the current problems of LCA. One of the main problems is attributed to the gathering of data [5]. In order to execute a meaningful LCA, it is vital to collect accurate and precise data, which can be rather difficult depending on the dimensions of a product lifecycle and the scope of the LCA [4]. Reasons for inadequate LCA results are poor data quality, invalid data, incomplete data or oversimplified data models, to name a few [5]. One possible solution will be examined later in this study. Another problem is the comparability of LCAs. Despite already existing standardisations like the International Organization for Standardisation (ISO), there are still areas of arbitrariness in making LCAs, for instance, non-transparent assumptions in impact modelling or obscure methods of measuring [5]. A further issue with LCA is its central focus on environmental impact with a lack of consideration for social aspects e.g. labour conditions or fair wages [4]. In consideration of the above, LCA is limited to providing comprehensive insights into the sustainability of a product lifecycle [4]. It is deficient in its ability to provide social and governmental insights [4].

As Hauschild et al. stated [4], there are various reasons why companies or other organisations should face these challenges to benefit from LCAs. Although LCA is traditionally used for assessing only one product, one can recognise that the trend goes towards the corporate level to reflect the performance of the whole company in sustainability matters. Some of these categories are carbon footprint, freshwater footprint or waste generation. It is reasonable to assume that environmental impact guidelines will steadily develop in the future. Using LCAs can have a noticeable advantageous impact on a company's marketing and image. In the modern economic world, stakeholders, including customers, have to place a higher value on these attributes than ever before, due to the growing climate change. The following chapter will examine these advantages in greater detail.

As mentioned in the structure of LCA, the third LCA phase uses a software to calculate und translate data into environmental impact. Due to the large amount of data required in order to perform a comprehensive LCA, the decision of which software to use is essential [2]. A variety of LCA software solutions are currently available on the market, each of them focusing on different aspects. Therefore, each software package has advantages and disadvantages in terms of costs and functionalities [2].

Table 2 briefly lists three major LCA tools. The selection of these three tools is based on their distinct capabilities, which enable them to meet the demands of a wide-ranging user base.

Table 2 LCA Tools [5–7]

Publisher	Software name	Description
Sphera (formerly GaBi)	LCA For Experts	- Contains more than 20 sector-specific databases - Enables fact-based decision-making
U.S. Department of Energy	Greet	- Assesses a broad range of environmental impacts - To guide decision making in research, development, and regulations
OpenLCA	OpenLCA	- Free to use, open-source LCA software - Professional ecological, social, and economic assessments

1.2 Environmental, Social and Governance reporting

"More than 90 percent of S&P 500 companies now publish ESG reports in some form" [8] and the percentage is expected to rise even further in the near future.

An ESG Reporting can be defined as a voluntary report that consists of three individual pillars, environmental (E), social (S) and governance (G) [9]. The primary objective of the report is to pursue shareholder value. Companies should become environmentally and socially accountable by reporting not only financial but also non-financial data [10]. This means that an ESG report is not really an essential factor for the success of the company, but its importance should not be underestimated.

First of all, an appealing business model attracts investors and customers. It may not be the main factor, but it is still crucial for the customers decision whether to purchase from a business or industry which is acting in a way that is fair, appropriate, and deserving of trust or not [8]. By acting appropriately companies are not only gaining trust of their customers and investors but also improve their brand reputation which can lead to a competitive advantage in comparison to competitors within the industry.

Secondly, a more transparent disclosure of the company's procedures is intended to create an incentive for more environmentally conscious behaviour and better working conditions within the enterprises. Therefore, the focus of an ESG is to have a positive impact on sustainability including the reduction of carbon emissions and improvement of labour conditions, employment diversity and governance practices [10].

An ESG report does not only benefit companies but also contributes to improved working conditions and greater sustainability. However, a critical evaluation of ESG reporting reveals certain areas for improvement. It is often stated that the data in ESG reports have no measurement standards [11] which leads to various problems such as inconsistency [12]. There are several units of measure to display the same sort of criteria. For example, to measure the employee health and safety there are multiple common metrics a company could use listed in Table 3.

Table 3 Different ESG standards in metrics and units [12]

Metric	Unit
Number of accidents with fatal consequences	Number
Rate of injury per 200,000 hours worked	Number (ratio)
Occupational injury rate-related fatalities	Number
Lost-time incident frequency rate	Percentage
Total case incident rate	Percentage

These metrics in Table 3 cover the same topic but are not at all comparable. The data is leading to different results even though they all want to express the health and safety of employees [12]. That leads to the result that companies can search for the measurements where they perform best, because there is no standard, which is prescribed at least within the industry. A study revealed that the correlation coefficient of ESG is on average by only 54 percent [8, 13]. ESG metrics significantly differ across providers and are not yet transparent or standardised. This indicates a lack of comparability between the companies.

Kotsantonis et al. stated that another problem that comes with the lack of standardisation in ESG reports is missing data [12]. Either the companies are not publishing regularly so stakeholders are forced to work with outdated data, or they publish incomplete reports. Due to voluntary nature of publishing an ESG report many companies mainly disclose positive data, while negative results were hidden by different measurements, as mentioned before, or completely ignored. A study revealed that approximately 50% of the considered companies report their employees' health and safety data. However, only 15% of these companies disclose their lost time incident rate and workplace fatalities.

The lack of standardisation in ESG reports contributes to Greenwashing [8]. As most of companies disclose only positive information, competitors feel pressured to do the same. The freedom companies currently have in creating their ESG reports leads to an absence of transparency and comparability [10]. It is not possible for stakeholders to trace the origin of the data, which makes it easy to manipulate [14]. To ensure a fair and accurate comparison of industry competitors, it is essential to establish a standard of measurement. This standard is necessary to identify and differentiate between positive and negative data. Currently, this distinction is not readily apparent, particularly to stakeholders who lack familiarity with these subjects [12].

To resolve the current problems of ESG reports, mandatory standards are an effective tool for increasing the number of disclosed ESG metrics. In the near future, the implementation of several directives will assist in resolving these issues. The upcoming changes and their impact on ESG reports will be discussed in chapter 1.4.

While the current ESG Report is beneficial, its voluntary nature and the significant amount of data required lead many smaller companies to prioritize investing in employee wages or product development [10]. Consequently, the allocation of financial resources to ESG reporting may be less efficient for these companies. Additionally, there is currently no evidence that ESG has a relevant impact on a company's financial performance [8]. While it is challenging to measure, the impact is undoubtedly significant, though not necessarily quantitative. This impact is primarily reputational for large enterprises [8]. ESG can have a greater impact when there is a uniform standard, which can lead to a higher willingness among companies to disclose an ESG report. Eventually, this contributes to the goal of enhancing sustainability within enterprises [10]. The requirement for companies to disclose comparable reports encourages them to improve their performance and achieve better scores.

In the second part, this study will propose an improvement to the ESG report to address the current issues. While reliability has not been fully established yet, implementing these improvements could enhance the trustworthiness and reputation of the ESG report.

1.3 Current combination of LCA and ESG

This section explores potential benefits associated with the integration of LCA data in ESG reports. Separating ESG reports into its components “E”, “S” and “G”, LCA provides advantages for all these three categories.

Beginning with the first and most striking aspect: The environment. Life Cycle Assessments collect and quantify environmental impact data [15]. This data can subsequently be integrated into ESG reports [3]. This practice can be observed in several companies, for example Shell Energy Europa Limited or RWE Supply & Trading GmbH [16, 17]. By assessing the carbon intensity of products and services, Shell Energy Europa Limited is able to track carbon emissions, to persue research and investments in lower-carbon solutions. RWE Supply & Trading GmbH utilises LCA for more informed decision-making about future projects and the development of sustainable trading portfolios. Furthermore, the utilisation of LCA software enables companies and other organisations to set informed sustainability goals and monitor their progress [3]. This integration facilitates a more comprehensive and accurate illustration of the environmental performance of a company [18]. It is notable that LCA has a strong synergy with the environmental dimension of ESG reports.

A problem that arises is that LCA focuses on environmental aspects of a product, while ESG covers a broader range of disclosures for an entire company. The primary challenge lies in the quantification of social and governance data [15]. The present state of research has already developed Social LCAs (S-LCA), which expand the traditional LCA including social dimensions to assess social impacts across the entire supply chain [15]. These extended assessments evaluate characteristics like labour conditions, human rights, and social risks [15]. The establishment of consistent key figures in the social and governance sectors is a major challenge [15]. One can conclude that Social LCA can contribute to the enhancement of the comprehensiveness of ESG reports. However, one must acknowledge that these results are often characterised by a certain degree of vagueness and lack of precision when compared to the environmental results [15].

Similar difficulties are also being encountered in the context of governance [15]. It has been determined that measuring, collecting, and quantifying comparable data in the governance domain is a complex undertaking, considering that companies are structured differently and are highly individual [3]. Assessments in the area of governance concentrate on enhancing transparency and traceability in supply chains and across corporate entities [3]. In this context, ESG reports will benefit from more accurate documentation, which will ultimately have a positive effect on the company's stakeholders [3].

With the global shift from voluntary to mandatory sustainability reporting, many stakeholders recognise the significance of sustainability [15]. Despite these stated challenges mentioned in the last two paragraphs, companies could derive advantages over their competitors, by integrating LCA into ESG reports [3, 18]. The most recognisable key advantage is that companies demonstrate a strong commitment to sustainability, thereby enhancing their sustainability image [18]. This integration can facilitate the identification of the most critical parts of the value chain, and thus the selection of environmentally responsible suppliers to improve the ESG score [18]. In order to address the increasing demand of stakeholders, the combination of LCA and ESG can enhance credibility and rigor in sustainable reporting, by providing quantifiable, science-based environmental impact data throughout a product's lifecycle [18]. Furthermore, companies benefit from improved decision-making processes, better identification and management of risks and increased stakeholder confidence [18]. Companies that proactively embrace this trend will be better positioned to meet evolving expectations from stakeholders and governance [18]. The combination of LCA and ESG reporting facilitates the creation of long-term value for businesses and stakeholders and drives improvements at the corporate level [18].

In summary, it can be observed that a synergy exists between LCA and ESG reporting [18]. The integration of LCA has been demonstrated to significantly enhance such reports, thereby providing valuable insights for companies seeking to improve their sustainability performance [18].

1.4 Standardisation of ESG data

For an extended period, a consistent and uniform standard for the disclosure of environmental, social, and governmental data has been absent. There are a variety of voluntary methods for reporting these data, including Global Reporting Initiative (GRI), The International Integrated Reporting Council (IIRC), International Sustainability Standards Board (ISSB), and Sustainability Accounting Standards Board (SASB). GRI has been the most famous one with its broad scope in e.g. tax transparency, water and effluent management, occupational safety and health, waste management and a range of other subjects [19]. However, instead of developing a divergent standard for corporations, there rather has been a fragmentation in the way of reporting these data [20]. In relation to the standards mentioned, these are applicable as a guideline for a compliant Non-Financial Reporting Directive (NFRD) [21]. NFRD was initiated in 2014, required 11,600 companies to disclose non-financial information, supplemented by non-binding guidelines, including the latest on corporate climate-related information reporting [22]. In order to create homogeneity, the European Parliament and the Council established the 2022 Corporate Sustainability Reporting Directive (CSRD), which aligns with the NFRD, to obligate all major, European companies disclosing data regarding their non-financial performances beginning from 2024 onwards [21]. Following the introduction of the CSRD and the achievement of uniform standards, the scope was expanded to encompass 49,000 companies [21]. The resulting goal was to strengthen the ability to make generally sustainable investments [21]. However, all companies should contribute on an effectively sustainable growth to gain transparency in the supply chain, mandating stakeholder engagement, and incorporating the double-materiality, the Corporate Sustainability Reporting Directive wants to approach a climate-neutral Europe [23]. This measure is expected to reduce the risk of greenwashing and achieving a common definition of sustainability within the companies [20].

The CSRD's introduction has also resulted in the establishment of European Sustainability Reporting Standards (ESRS), a uniform standard for the disclosure of ESG data, which define the measurements that must be reported [23]. They also consider ISSB and GRI data to ensure a high degree of interoperability between EU and global standards. In addition, unnecessary double reporting by companies is thereby prevented [24]. It is mandatory for the affected companies to disclose annually ESG data [21]. This includes greenhouse gas emissions, energy and water consumption, biodiversity and ecosystems or disposal for the environmental, diversity, health and safety of employees or gender-specific remuneration for the social and incidents of corruption for governmental aspects [25].

How can these ESRS data be used in ESG reports? The CSRD provides for the publication of more specific ESG data from companies to ensure standardised and transparent comparability. However, it does not yet appear based on our research that there is a combination within CSRD and ESG-Reports. This result is due to the fact that ESRS has been implemented in 2024, and there is currently no data from an ESG report using ESRS. In the near future, there may be more data combining ESRS and ESG. From a theoretical standpoint, the combination of these two models is possible due to overlaps between them. A possible approach of creating a standardised ESG report including ESRS data is explained below.

1.5 Research Gap

Table 4 summarises all the gaps identified in the literature review of the individual topics. These have already been described in previous chapters and are presented here again in table form.

Table 4 Research Gap

Source	Topic	Problem	Research Gap
[4, 8, 12, 15, 26]	Data collection	Missing and inconsistent data collection	Standardised, tamper-proof, direct acquisition of ESG data.
[10, 11, 27]	Data storage	No traceability and manipulability	Transparent, decentralised, tamper-proof data storage.
[10, 11]	Data validation	No data inspection	Automatic and secure validation of data.
[4, 26]	Data processing	High effort, complex data sets	More efficient modelling, sorting, and evaluation of ESG data.
[8, 11, 12]	Automated ESG	Greenwashing ESG, no comparability	Comparable and automated ESG report.

2. Optimisation of ESG reports

The following section outlines strategies for enhancing the quality of ESG reports to ensure they are free of the identified issues.

This study proposes a model illustrated in Figure 1 to solve the previously stated problems (Table 4) and align common ideas in manufacturing sectors. The model is based on existing research, which has already combined smart sensors, blockchain and smart contracts for LCA [28]. The research study of Ramesh et al. [29] collaborated LCA and AI, both of which were tested in practice and are feasible. The following model combines these two functional approaches and extends them regarding the utilisation of standardised ESG data. The proposed model is structured as follows:

Firstly, the following section presents the data requirements and how they will be collected. Afterwards, the model displays how the data can be stored in a transparent and public form. Finally, AI is integrated in LCAs to obtain an automated and standardised ESG report. The steps are outlined below and demonstrated using a practical case from a manufacturing company. Given that Tesla is frequently referenced in the chosen sources, the electric vehicle company serves as a representative example.

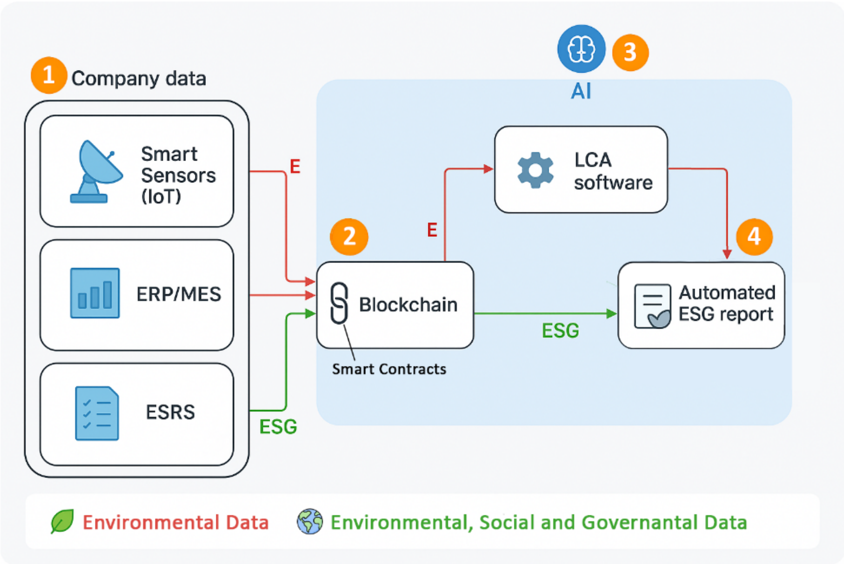

Figure 1. A proposed, optimised system for automated ESG reports

2.1 Data requirements

As shown in the first step of Figure 1, a key part in this process is the selection of uniform data, which will serve as a foundation for the creation of a standardised ESG report. This data must be reported accurately according to established methodologies [11]. The use of predefined standards, such as ESRS, can assist companies in collecting the necessary data.

There are two options for collecting the predefined data properly. The data is either already in the company's possession, or it must be collected.

The first option is clearly the more convenient choice. If the data is already available, such as for an ESRS, it can be directly uploaded into a storage system. Additionally, ESG data might already be present in the corporate MES or ERP system, which could also be utilised to generate the ESG report. Enterprise resource planning (ERP) systems are software solutions that address all aspects of a company's operations [30]. However, manufacturing execution systems (MES) are software designed for the management of production processes, with a primary function of controlling the conversion of raw materials into finished products [31].

In the event that data is incomplete, it is crucial to collect it in a way that is both transparent and free from any potentially fraudulent activities. To ensure the integrity of this process, companies within the same industry can collaborate to collect and store this data directly in a storage system, thereby eliminating any external or internal influences that could compromise the accuracy or authenticity of the information. This technology is named smart sensors. Smart sensors collect and store data at the point of occurrence, with no adjustments applied. These sensors can be strategically placed within machines in production processes. They are used to measure and calculate greenhouse gas emissions, water consumption, and energy consumption, among other metrics [28].

Tesla, for example, could now apply smart sensors into their manufacturing process to collect real-time data like electricity, water usage and carbon emissions. Thus, the only issue that remains is the implementation of the sensors, rather than the general issue of collecting these data.

One issue that occurs when collecting ESG data is the difficulty of measuring social and governmental data, due to the complication of quantifying such data [10]. Therefore, smart sensors are only capable of collecting data related to the Environmental pillar [28], which is more quantifiable. In the context of a MES or ERP system, there is typically limited integration of social and governmental data, as the primary objective is to focus on value chain data. As a result, this data is collected manually for an ESRS and could be reused in an ESG report (Figure 1).

The collected data can be stored in a variety of ways, including databases and blockchain. Uploading data into a blockchain offers several advantages, including addressing some of the issues associated with ESG reports. These advantages will be discussed in more detail below.

2.2 Data storage

To overcome the problem of manipulation and the traceability of ESG data, the blockchain technology serves as a potential solution. In addition to cryptocurrencies, it can also be used to verify and store data [28].

Blockchain is a technology that stores and handles a digital ledger of transactions [32]. These transactions can be divided into two categories: informative and financial data. They will be stored in blocks, which are linked together in a chain [32]. When a transaction, such as the transfer of data, for example energy consumption, is to be recorded, it must go through the blockchain process. This involves representing the transaction online as a block, which is shared to every party in the existing network. Subsequent to this, the network's verification process begins. It utilises a consensus mechanism based on cryptography, which serves to confirm the validity of each transaction [33]. This procedure allows the block to be added to the chain [33].

To obtain an automated ESG report a Blockchain is set up to store the previously mentioned data (Function 2 in Figure 1). Eventually, this data is then uploaded by companies within the same sector. Before the data is transferred to the blockchain, smart contracts are in place to validate them. Smart contracts are computer protocols stored on a blockchain that are automatically executed when predetermined terms and conditions are met [32]. According to [28] these serve as a kind of filter to automate key functions of the process:

1. verification of ESG data sources is undertaken
2. a comparison of data with predefined rules is made
3. reporting of anomalies is conducted

This approach has already been described by Jiang et al. [28] using the example of an electric vehicle from Tesla. The study performed by Jiang et al. demonstrates that the integration of blockchain technology with the interaction of LCA can be useful to generate an ESG report, thereby providing environmental impacts of companies across the value chain.

As illustrated in Figure 1, function 1 restricts the upload of data to the blockchain only to authorised participants, for example companies and upstream and downstream partners in the value chain. All others are prevented from uploading. This procedure is intended to prevent the storage of irrelevant data from other sources within the blockchain. For functions two and three, smart contracts are able to identify abnormal values based on predetermined rules or standards, for example if a value sent to a smart contract is above a threshold, it is considered abnormal, and an alert is sent. This is also essential for the cross-validation application of the system, as the mismatch of relevant data reported by two companies for the same materials or products may indicate a suspicious disclosure. Any discrepancy indicates a potential error or fraudulent activity related to this transaction that should not be recorded on the Blockchain.

The utilisation of the integrated blockchain in this process has several advantages.

Due to the cross validation of smart contracts, the blockchain architecture enables a flawless storage system for data [28]. This serves to reduce the human error rate and avoid manipulation while uploading the data [14].

Since every transaction is recorded, traceability and thus liability is granted. This concept enhances trust and transparency towards stakeholders and improves the seriousness of companies [34]. The decentralisation characteristic of a blockchain strengthens the transparency aspect, since a transaction can be executed between any two peers without the authentication of a central agency [33]. Additionally, every stakeholder has the possibility to access the data as it is stored online.

Furthermore, another advantage of decentralisation is that the functionality of the network remains intact even in the event of a cyberattack or failure of a participating party [34]. Thus, the blockchain system prevents data loss.

In addition to the advantages associated with blockchain, there is also a disadvantage regarding this technology. Scalability presents a considerable challenge [33]. Given the necessity of storing each transaction for validation purposes, the blockchain becomes increasingly complex.

2.3 Data processing using AI

In the context of LCA software the implementation of AI appears to be a highly promising approach [29]. Artificial Intelligence (AI) received a lot of attention in the last years and can be utilised as a strong tool to enhance processes and methodologies. Artificial Intelligence can be described as the science and engineering of making intelligent machines, especially intelligent computer programs, with the ability to achieve goals [36]. AI can be divided into several categories, including Machine Learning (ML) and Deep Learning (DL), which are used in applications like self-driving cars. Another key area is Natural Language Processing (NLP) and Large Language Models (LLMs), found in technologies such as Apple’s Siri or OpenAI’s ChatGPT among numerous other categories [35]. The potential applications of AI encompass a wide range of disciplines and sectors, including economy, medicine, education and research and in this particular report: Environmental impacts [35].

Building on existing research from Ramesh et al. [29], this work presents an optimised LCA software solution by incorporating Machine Learning (ML) and Deep Learning (DL) [36]. One core reason to implement ML into LCA is the superior handling of large and complex data sets [29]. AI models, such as Residual Neural Networks (ResNet) can streamline data processing for complex datasets by learning residual functions [29] that enhance computational efficiency for large-scale life cycle inventories [29]. Considering the amount of input data from all the mentioned sources, it is essential for the AI enhanced LCA software to be capable of effectively processing this data. ML itself can process large data sets to identify patterns, which is a limitation in traditional LCA approaches [29, 37]. This characteristic is vital for the presented model (Step 3 of Figure 1), since the LCA software must manage a large amount of data input. As stated in the previous section about LCA, conventional LCA software is struggling with uncertainties and predictions due to a lack of data input. AI models, particularly Machine Learning (ML) algorithms, have demonstrated superior accuracy in predicting environmental impacts through the process of learning from historical data and extrapolating insights [29, 37]. As illustrated in Figure 2, traditional LCA solutions achieve an accuracy of 80%. The AI models Artificial Neural Networks (ANN), Convolutional Neural Networks (CNN) and Residual Neural Networks (ResNet) excel conventional LCA in terms of accuracy by 10-12%. [29]

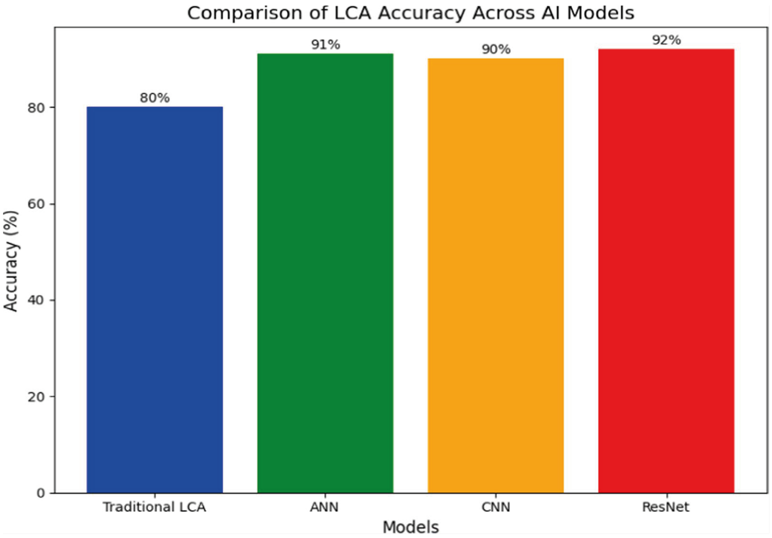

Figure 2 Comparison of LCA Accuracy Across AI Models [29]

AI applies probabilistic approaches, which enables more precise identification of environmental impacts associated with the various stages across the lifecycle of products and supply chains [29]. This characteristic facilitates the creation of more accurate ESG reports. Traditional LCA software solutions typically model in linear, simplified relationships between multiple inputs such as material usage and energy consumption, and outputs e.g. carbon footprint [29]. Nonetheless, certain products and supply chains reveal nonlinear, more complex behavioural patterns and are highly interconnected [29]. Deep Learning applications, such as ANN and CNN, can handle these nonlinearities more successfully [29]. In order to boost the accuracy and comprehensiveness of an ESG report to an even higher extent, DL helps optimising the production process and managing the supply chain more efficiently than conventional LCA software [29]. This informed decision making enables improvements in product development and design [29]. In consideration of long-term durability, the integration of AI has been demonstrated to enable autonomous learning of new information. [29, 37]. This continuous learning characteristic subsequently improves environmental impact predictions, which leads to an even more accurate LCA result [29, 37].

Despite all these advantages, there are challenges that must be taken into consideration. AI models require a large amount of datasets to be trained effectively [29]. In circumstances with limited data, these models may underperform or overfit [29]. Complex AI structures are often considered as “black boxes” [29]. The lack of transparency complicates the interpretation of the impact of individual variables within the model [29]. In addition, computational expense and cost are significant [29]. Furthermore, AI models often need modifications to effectively analyse tabular data, which is frequently encountered in LCA environments [29].

This work proposes that AI-enhanced LCA software utilises blockchain data as inputs. The AI-LCA software possesses the ability to autonomously determine and validate the specific required data for its assessment. The software processes the data inputs accordingly and more precise (Figure 2) and converts it into environmental impacts. In complex assessments, the software has the capacity to access databases such as Ecoinvent to get extra information for the calculations. Subsequent to the Life cycle assessment, the results are available for the creation of an automated and consistent ESG report.

Referring to the Tesla example, Tesla could develop and train an AI-based LCA software to benefit from the previously mentioned advantages, such as improved accuracy and more detailed insights in the supply chain.

Overall, AI-based LCA offers a significant improvement, especially with complex datasets in the field of environmental impact evaluation [29]. By leveraging advanced AI models, this work addresses the current limitations of traditional LCA methodologies and provide more accurate and comprehensive assessments [29].

2.4 Automated ESG report

The three components (Steps 1 to 3 of Figure 1) combined are leading to an automated ESG report for companies, which then is created with minimal effort. This ultimately standardises an ESG report and encourages companies to publish one, since the process is now simplified. In addition, this model resolves all the issues previously mentioned.

Inconsistent data is solved with a uniform standard that aligns with the ESRS standard. Additionally, AI helps to make the report less complex for companies. By entering the relevant data, companies can generate an ESG report automatically.

Missing data has also been an issue. The implementation of smart sensors now enables the collection of data at the moment of creation. The implementation of blockchain technology on the other hand ensures the integrity and transparency of data for stakeholders and creates comparability between companies within the same industry. This approach helps to prevent greenwashing.

In order to bring this concept to realisation, there are a number of prerequisites needed. To initiate the implementation process, the government should consider introducing legislation which will apply pressure on the companies. If one company were to implement this model, the issue of missing comparability would remain unresolved as long as the other companies in the industry did not follow suit.

Another challenge for the implementation will be the practical conduction. First, the blockchain and AI logic need to be implemented to ensure its functionality. Additionally, smart contracts must be programmed with consideration of the preselected data, which will eventually be in the report. Due to the different requirements of data within the sectors, a collaboration of the companies in the same industries would be necessary. They need to agree on the selection of relevant data.

As with any business model, there are some further challenges to consider. Firstly, as already mentioned before, the implementation will be complex and expensive. Thus, a strong effort needs to be made to persuade companies to implement this model. Smart sensors must be purchased and installed on the machines to collect the required data.

Moreover, companies may be hesitant to participate due to their inability to influence the later publication of the data.

A further limitation of the model is its broad focus on the company, not the product itself. For example, if a company outsources significant carbon emissions, it may present favourable statistics, even though it is responsible for a larger amount of emissions. A full integration of LCA into an ESG report would solve this problem, because it considers the entire lifecycle of a product, not only one production step. However, it has not yet been included into an ESG report. The main aspect in this regard is, as previously mentioned, the complex consolidation of ESG and LCA. This issue may be resolved in the future and could be included afterwards in this model.

3. Conclusion and outlook

The objective of this report is to encourage companies to make generally sustainable investments by means of corporate sustainability reporting. The analysis has shown that, while both ESG and LCA are well-established frameworks, their integration remains limited—particularly with regard to data consistency, standardisation, and technological implementation. This work also identified a need for automation in the process of creating ESG reports. To achieve this, it is necessary to improve several steps, such as the collection of data using Internet of things (IoT) devices e.g. smart sensors, the integration of data with manufacturing software systems such as ERP and MES, and the use of the implemented ESRS policy. In certain instances, processes may require a complete revision. This could include the creation of a unified standard for ESG reporting, the adoption of data storage technologies such as blockchain, and the integration of AI. The described model could be relevant for a wide range of industries, such as renewable energies, construction or the circular economy. Despite the fact that the extension is based on already existing and functional parts, the model still requires testing on its feasibility.

In view of the criticism of the automated ESG reporting process, there is the alternative of having a company's ESG report produced by an external auditor. This auditor would be tasked with the neutral review of the ESG data provided by the company and the determination of missing data. The auditor would thereby generate a uniform, standardised ESG report. The proposal of this report does not exclude the later integration of an external auditor into the model for verification purposes.

Overall, there has been extensive research on LCA and ESG, yet there are notable gaps when it comes to combining them, particularly in areas such as data collection, security, and validation. In this sense, the study offers a promising step towards more meaningful sustainability reporting. However, it is important to note that this approach may require expansion and refinement in order to achieve optimal outcomes.

References

[1] ISO, *ISO 14040:2006.* [Online]. Available: https://www.iso.org/standard/37456.html (accessed: Mar. 8 2025).

[2] D. R. Vieira, J. L. Calmon, and F. Z. Coelho, "Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review," *Construction and Building Materials*, vol. 124, pp. 656–666, 2016, doi: 10.1016/j.conbuildmat.2016.07.125.

[3] PricewaterhouseCoopers, *How life cycle assessments can unlock value and lead to more sustainable products.* [Online]. Available: https://www.pwc.com/us/en/services/esg/library/lca-sustainability.html (accessed: Mar. 8 2025).

[4] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, *Life Cycle Assessment*. Cham: Springer International Publishing, 2018.

[5] Sphera, *Software und Daten zur Lebenszyklusanalyse | Sphera (GaBi) | Sphera.* [Online]. Available: https://sphera.com/de/loesungen/product-stewardship/life-cycle-assessment-software-and-data/ (accessed: Mar. 8 2025).

[6] Energy.gov, *GREET.* [Online]. Available: https://www.energy.gov/eere/greet (accessed: Mar. 8 2025).

[7] *openLCA.org | openLCA is a free, professional Life Cycle Assessment (LCA) and footprint software with a broad range of features and many available databases, created by GreenDelta since 2006.* [Online]. Available: https://www.openlca.org/ (accessed: Mar. 8 2025).

[8] L. Pérez, Vivian Hunt, Dame, Samandari, Hamid, R. Nuttall, and K. Biniek, *Does ESG really matter—and why?* [Online]. Available: https://www.mckinsey.com/capabilities/sustainability/our-insights/does-esg-really-matter-and-why (accessed: Mar. 8 2025).

[9] Q. Cheng, Y. Lou, and M. Yang, "ESG Reporting Divergence," *SSRN Journal*, 2023, doi: 10.2139/ssrn.4565408.

[10] R. S. Kaplan and K. Ramanna, "How to Fix ESG Reporting," *SSRN Journal*, 2021, doi: 10.2139/ssrn.3900146.

[11] T. Cort and D. Esty, "ESG Standards: Looming Challenges and Pathways Forward," *Organization & Environment*, vol. 33, no. 4, pp. 491–510, 2020, doi: 10.1177/1086026620945342.

[12] S. Kotsantonis and G. Serafeim, "Four Things No One Will Tell You About ESG Data," *J Applied Corp Finance*, vol. 31, no. 2, pp. 50–58, 2019, doi: 10.1111/jacf.12346.

[13] F. Berg, J. F. Kölbel, and R. Rigobon, "Aggregate Confusion: The Divergence of ESG Ratings," *Review of Finance*, vol. 26, no. 6, pp. 1315–1344, 2022, doi: 10.1093/rof/rfac033.

[14] K. R. Kirchhoff, S. Niefünd, and J. A. von Pressentin, *ESG: Nachhaltigkeit als strategischer Erfolgsfaktor.* Wiesbaden: Springer Fachmedien Wiesbaden, 2024.

[15] S. P. Ngan, S. L. Ngan, and H. L. Lam, *A Holistic Approach to Sustainability Reporting: Integrating Social and Governance Dimensions in Life Cycle Assessment*. AIDIC The Italian Association of Chemical Engineering: Chemical Engineering Transactions, 2024.

[16] Shell, *Shell Energy Europe | Shell Global.* [Online]. Available: https://www.shell.com/shellenergy/shell-energy-europe.html (accessed: Apr. 9 2025).

[17] Rwe, *Das ist RWE.* [Online]. Available: https://www.rwe.com/ (accessed: Apr. 9 2025).

[18] M. Müller *et al., Eds., KNOWCON 2023. Knowledge on Economics and Management: Conference Proceedings*. Křížkovského 8, 771 47 Olomouc: Univerzita Palackého v Olomouci, Dec. 2023 - Dec. 2023.

[19] I. Zenkina, "Ensuring the transparency of ESG reporting based on the development of its standardization," *E3S Web Conf.*, vol. 371, p. 5077, 2023, doi: 10.1051/e3sconf/202337105077.

[20] E. Barman, "Doing Well by Doing Good: A Comparative Analysis of ESG Standards for Responsible Investment," in *Advances in Strategic Management, Sustainability, Stakeholder Governance, and Corporate Social Responsibility*, S. Dorobantu, R. V. Aguilera, J. Luo, and F. J. Milliken, Eds.: Emerald Publishing Limited, 2018, pp. 289–311.

[21] H.-V. Nora, "Non-financial Reporting Directive," 2021. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/654213/EPRS_BRI(2021)654213_EN.pdf

[22] A. Pietrancosta and A. Des Marraud Grottes, "ESG Trends – What the Boards of All Companies Should Know About ESG Regulatory Trends in Europe," *SSRN Journal*, 2022, doi: 10.2139/ssrn.4206521.

[23] M. Szafarska-Ponińska, *CSRD*, 2024. Accessed: Mar. 11 2025. [Online]. Available: https://assets.zyrosite.com/amqprpz6kzhxxova/csrd-impact-report-ykb69z7pexiez6o5.pdf

[24] Directorate-General for Financial Stability, Financial Services and Capital Markets Union, *The Commission adopts the European Sustainability Reporting Standards.* [Online]. Available: https://finance.ec.europa.eu/news/commission-adopts-european-sustainability-reporting-standards-2023-07-31_en (accessed: Mar. 8 2025).

[25] *ESRS: Ein Leitfaden zu den wichtigsten CSRD-Kennzahlen | Atlas Metrics.* [Online]. Available: https://www.atlasmetrics.io/de/blog/csrd-esrs (accessed: Mar. 8 2025).

[26] S. Ross, D. Evans, and M. Webber, "How LCA studies deal with uncertainty," *Int J LCA*, vol. 7, no. 1, 2002, doi: 10.1007/BF02978909.

[27] A. Kumar, T. King, and M. Ranta, "Corporate governance characteristics and involvement in ESG activities: current trends and research directions," *CG*, vol. 24, no. 8, pp. 175–209, 2024, doi: 10.1108/CG-09-2023-0397.

[28] L. Jiang, Y. Gu, W. Yu, and J. Dai, "Blockchain-based Life Cycle Assessment System for ESG Reporting," *SSRN Journal*, 2022, doi: 10.2139/ssrn.4121907.

[29] V. Ramesh, B. Muthramu, and D. Rebekhal, "A review of sustainability assessment of geopolymer concrete through AI-based life cycle analysis," *AI Civ. Eng.*, vol. 4, no. 1, 2025, doi: 10.1007/s43503-024-00045-3.

[30] SAP, *What is ERP? The Essential Guide | SAP.* [Online]. Available: https://www.sap.com/products/erp/what-is-erp.html (accessed: Mar. 8 2025).

[31] SAP, *Was ist ein Manufacturing Execution System (MES)?* [Online]. Available: https://www.sap.com/germany/products/scm/execution-mes/what-is-mes.html (accessed: Mar. 8 2025).

[32] P. Treleaven, R. Gendal Brown, and D. Yang, "Blockchain Technology in Finance," *Computer*, vol. 50, no. 9, pp. 14–17, 2017, doi: 10.1109/MC.2017.3571047.

[33] Z. Zheng, S. Xie, H. N. Dai, X. Chen, and H. Wang, "Blockchain challenges and opportunities: a survey," *IJWGS*, vol. 14, no. 4, p. 352, 2018, doi: 10.1504/IJWGS.2018.095647.

[34] M. Nofer, P. Gomber, O. Hinz, and D. Schiereck, "Blockchain," *Bus Inf Syst Eng*, vol. 59, no. 3, pp. 183–187, 2017, doi: 10.1007/s12599-017-0467-3.

[35] R. S. T. Lee, *Artificial Intelligence in Daily Life.* Singapore: Springer Singapore, 2020.

[36] J. McCarthy, *What is artificial intelligence*, 2007. [Online]. Available: https://trilliumdynamix.com/jmc/whatisai.pdf
[37] K. E. Bassey, Ayanwunmi Rebecca Juliet, and Akindipe O. Stephen, *AI-Enhanced lifecycle assessment of renewable energy systems*, 2024. [Online]. Available: https://www.researchgate.net/profile/kelvin-bassey-2/publication/383874831_ai-enhanced_lifecycle_assessment_of_renewable_energy_systems/links/66df27f164f7bf7b19a2e022/ai-enhanced-lifecycle-assessment-of-renewable-energy-systems.pdf