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A Critical Evaluation of Methods for the Assessment of Environmental Sustainability of Engineering Supply Chains

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Abstract: Engineering supply chains face increasing pressure to minimize carbon emissions in line with international climate targets. However, existing approaches for assessing carbon emissions are limited in their ability to capture the complexity of engineering supply chains, particularly during early design stages. Methods such as Life Cycle Impact Assessment and standards including ISO 14064 provide general guidance but lack methodological specificity for capturing indirect carbon emissions and supporting early decision-making. This paper presents a critical review of carbon emissions assessment methods applicable to engineering supply chains. A structured literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses approach to ensure transparency and reproducibility. The analysis evaluates the applicability of current methods, their integration with engineering design processes, and their feasibility during early design stages when data are limited. Challenges are identified, including the neglect of indirect emissions, complex system boundary definitions, and the lack of support for iterative design workflows. To address the challenges, methodological requirements are proposed for future carbon assessment methods. These include the capacity to handle data uncertainty, alignment with design decisions, and definition of appropriate system boundaries. The findings highlight the need for a carbon emissions assessment approach that can operate under limited data conditions, support early design decision-making, and capture the complexity of engineering supply chains. The novelty of this study lies in its review of existing methods and standards to highlight methodological requirements that allow carbon assessment during early design stages.

Keywords: carbon emissions assessment, Scope 1, 2, and 3 emissions, early design decision, early-stage life cycle assessment, methodological framework

1. Introduction

Environmental sustainability is an important issue, especially for manufacturing industries, where increasing environmental awareness has affected global markets [1]. This is reflected in increasing global awareness, regulatory pressure, and customer demands for environmentally sustainable products. These factors have driven engineering companies to implement environmentally sustainable strategies, particularly in minimizing carbon emissions. The engineering and manufacturing industries are expected to play an important role in minimizing carbon emissions because of their current contributions. For example, the United Kingdom emits approximately 350 million tons of carbon dioxide annually, with plans to reduce this to zero by 2050 under the Paris Agreement on climate change [2]. In response to the United Nations Sustainable Development Goals (SDGs), there is growing pressure on manufacturing industries to implement environmental sustainability in their performance, specifically through minimizing carbon emissions. The SDGs were introduced in 2015 as part of the 2030 Agenda for Sustainable Development, where these goals were established to address global challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice. The SDGs aim to create a blueprint for achieving a more sustainable future for all [3].

Engineering supply chains are different from conventional supply chains due to their multi-tiered, globally distributed networks shaped by design decisions. These complexities include the integration of design-driven material selection, the coordination of multi-tier suppliers located across the globe, and the environmental impacts of transporting parts/components across international boundaries [4]. Early design decisions, for example, material selection, transport, and manufacturing processes, influence the carbon emissions of a product [5]. However, during these stages, detailed data are limited, which causes challenges in assessing carbon emissions. Despite existing efforts to optimize supply chains for cost and efficiency, sustainability considerations are often overlooked or applied too late in the product development process for significant improvements to be realized [6].

There are existing approaches to assess environmental impact in supply chains, for example, Life Cycle Impact Assessment (LCIA) [7]. While LCIA provides structured methodologies for assessing carbon emissions across a product's life cycle, it has limitations when applied to engineering supply chains. These

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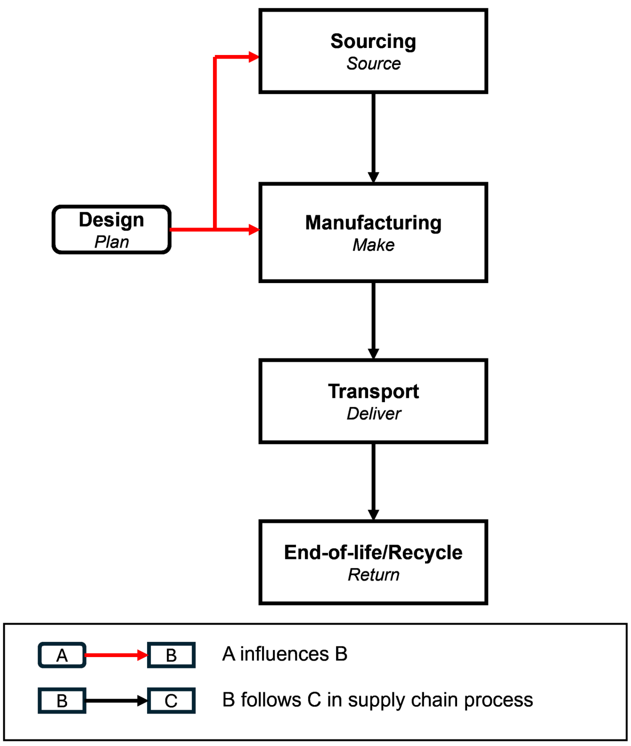
approaches require detailed input data, which is often unavailable during the early design stages, yet these stages are critical for improving environmental performance. This creates a gap between existing carbon emissions assessment methods and the need for tools to support early design decisions related to the environmental sustainability of manufacturing and production processes. Another gap in existing methods for the assessment of carbon emissions is the underrepresentation of Scope 3 emissions [8]. According to the Greenhouse Gas (GHG) Protocol, carbon emissions are classified into three categories: Scope 1 emissions are direct emissions from sources owned or controlled by the organization; Scope 2 emissions are indirect emissions from purchased electricity, heating, or cooling consumed by the organization; and Scope 3 emissions refer to carbon emissions embodied in the production of products and from sources outside the organization's control [9], including both upstream and downstream activities such as raw material extraction, transport, and product disposal. Despite often being the biggest contributors to carbon emissions in engineering supply chains, Scope 3 is frequently excluded owing to its complexity [9].

International standards such as ISO 14064 and ISO 14067 are intended to address the SDGs by offering guidelines for carbon emissions assessment. These standards emphasize transparency, consistency, accuracy, and completeness in carbon emissions calculations. They guide organizations in conducting detailed and accurate carbon emissions analyses, ensuring that all relevant emissions are accounted for. While existing methodologies for assessing carbon emissions, such as LCIA and ISO-based standards, offer frameworks and guidelines, they typically focus on the product level and assume well-defined processes. These methods have limited capability to capture the distributed and design-driven nature of engineering supply chains. Figure 1 [10] shows a representation of engineering supply chains based on the Supply Chain Operations Reference (SCOR) model. The SCOR model focuses on supply chain management from an operational process perspective and includes physical transactions, market interactions, and customer interactions [8]. However, when applied to carbon emissions assessment, existing methods are lacking when addressing the complexity depicted in the SCOR structure. This includes material selection decisions made during early design stages, coordination across global suppliers, and the carbon impact of transport routes [4]. These challenges highlight the need for a holistic approach to carbon emissions assessment, one that is responsive to the configuration and dynamics of engineering supply chains and applicable even when detailed data are not available. This review aims to address the gap in existing methods by identifying limitations of current carbon assessment approaches and highlighting requirements for new methods that can operate during early design stages, even when data availability is limited. To summarize, this study contributes by integrating engineering design perspectives with carbon emissions assessment frameworks such as ISO 14064/14067 and the GHG Protocol, highlighting methodological requirements that link early design decision-making with sustainability. The added value of this paper lies in providing a foundation for developing carbon assessment methods that can assess carbon emissions with limited design data and align sustainability assessments with early design decisions.

Figure 1
Engineering supply chains based on the Supply Chain Operations Reference (SCOR) model



2. Review of Existing Carbon Emissions Assessment Methods

Numerous methods have been developed to assess carbon emissions in supply chains, including LCIA, Eco-Indicator 99 (EI99), international standards such as ISO 14064 and ISO 14067, and emerging digital technologies. However, their suitability for engineering supply chains, particularly during early design stages, remains limited. This section presents a critical review of these methods with a focus on their applicability to design-driven decisions where data availability is often constrained and system complexity is high.

To guide the review, a structured literature search was conducted, followed by content analysis to identify publication trends, thematic focus, and methodological gaps. The literature search was conducted by implementing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. Databases (Scopus, Web of Science, and Science Direct) were searched using keywords related to "carbon emissions," "engineering supply chain," "early design," and "ISO standards." The inclusion criteria comprised peer-reviewed journal articles published between 2010 and 2025 that addressed carbon assessment in engineering or manufacturing contexts. After screening 436 records, 74 studies were analyzed in depth. This process provides a foundation for identifying methodological gaps. The results of this analysis provide context for selecting the reviewed methods and highlight the dominant sustainability concerns addressed in existing research.

2.1. Trends in literature

Over the past decade, interest in environmental sustainability within manufacturing and engineering supply chains has grown significantly. This rise is largely influenced by international initiatives such as the Paris Agreement and the United Nations' SDGs, which have encouraged organizations to reduce carbon emissions and disclose environmental performance [2, 3].

Figure 2 [11] shows the increase in research publications related to carbon emissions and supply chains from 2015 onward. This trend reflects growing academic and industrial focus on the development of assessment methods for carbon emissions, particularly in response to increased regulatory pressure and stakeholder demand for low-carbon products.

Figure 2 shows the publication growth increases after 2020, coinciding with updates to ISO 14067 and the GHG Protocol Scope 3 guidance. This suggests that global policy and standardization activities influenced academic research directions. The upward trend also indicates a shift from product-level life cycle studies toward supply chain assessments that capture upstream and downstream carbon emissions.

To understand how environmental sustainability is addressed within product life cycles, an analysis was conducted to identify the types of sustainability parameters that are frequently discussed in the literature. As shown in Figure 3, raw materials, transport, and energy use during manufacturing are the most frequently cited environmental considerations. These correspond to design decisions that are typically made during the early stages of product development. However, existing carbon emissions assessment methods often require detailed data that are unavailable at this stage, for example, material selection, making it difficult for engineers to evaluate emissions trade-offs early in the design process. This trend in literature shows the need for carbon emissions assessment methods that support early design decisions, particularly in engineering supply chains where product configurations, sourcing, and transport strategies are still evolving.

Insights from Figures 2 and 3 indicate that existing research focus emphasizes operational carbon emissions and manufacturing efficiency, with less attention paid to early design decisions. This reinforces the motivation for a review that bridges engineering design decisions and carbon emissions.

2.2. Life Cycle Impact Assessment (LCIA)

LCIA is a widely used methodology for assessing environmental impacts across the full life cycle of a product. It provides a systematic approach for quantifying emissions from raw material extraction, manufacturing, use, and end-of-life disposal. Researchers have adapted LCIA in various ways to assess carbon emissions in engineering contexts.

For example, Wang et al. [7] proposed a model that assesses carbon emissions across five stages of the product life cycle (raw material extraction, manufacturing, transport, usage, and recycling), which emphasizes the importance of stage-by-stage analysis, and Zhang et al. [12] introduce a method for calculating

Figure 2
Number of articles based on publication year

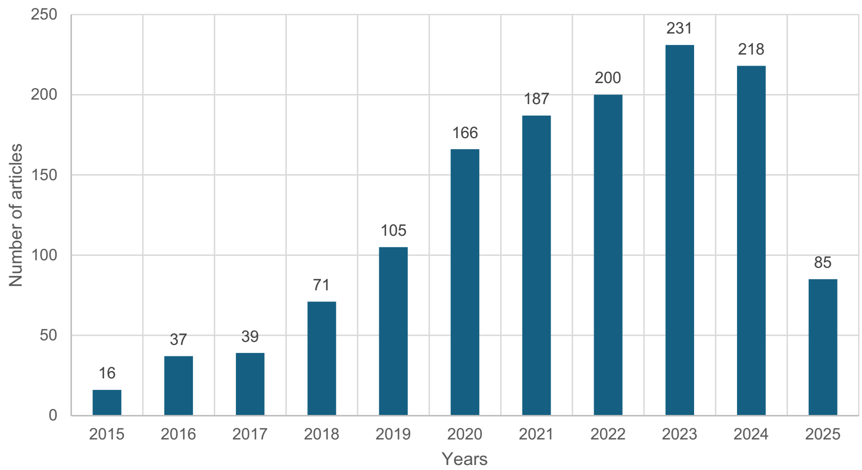
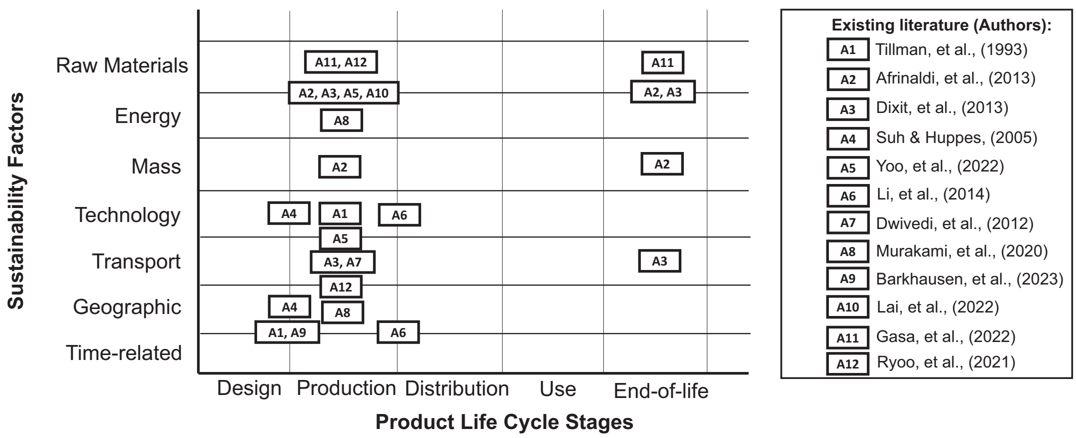


Figure 3
Analysis of the sustainability factors within the product life cycle stages



carbon emissions associated with the manufacturing processes of electrical machines, particularly focusing on industrial synchronous generators. The LCIA methodology encompasses three core analytical approaches: input–output analysis (IOA), life cycle assessment (LCA), and a hybrid method (IO-LCA) that combines the strengths of both IOA and LCA. Priarone and Ingarao [13] discuss the modeling of life cycle energy demand and carbon emissions in four stages: material production, manufacturing, transport, and usage, with a focus on the impact of life cycle energy demand and carbon emissions on metal-based components produced via conventional subtractive manufacturing and additive manufacturing processes. Zhang et al. [14] propose a quantification for variable carbon emissions of mechanical parts from raw material acquisition, manufacturing, and usage and focus on integrating material and structural optimization of mechanical parts to produce low-carbon designs of structural components. According to the authors, mechanical parts consume high amounts of energy and resources in the manufacturing stage, and this produces a large amount of carbon emissions. This method is more suitable for calculating carbon emissions for structural components rather than engineering supply chain processes because it needs data related to product module designs, which cannot be easily identified at an early stage of the design.

Song et al. [15] discuss carbon emissions structures in supply chains. In a similar way to Wang et al. [7], they define the supply chain as consisting of raw material extraction, production and manufacturing, transport, usage, and disposal and recycling. Using the idea of carbon emissions chains across supply chains, the authors introduce a decision-making method based on a mathematical approach where quantitative analysis is made based on existing data and evaluation from experts. The authors introduced a carbon footprint calculation method in a product carbon chain; hence, this method is only practical by constructing a product's carbon chain to define the supply chain boundaries. This method is ideal for engineering supply chains but needs more input data to determine the division of carbon source boundaries within a given supply chain. Zhou et al. [16] introduced a carbon emissions calculation model for material, energy, and waste for the part machining process that derives material carbon emissions from the (1) production of raw materials, (2) cutting tools, and (3) cutting fluid consumed in a process stage.

Mannheim [17] focused on LCA of plastic products by comparing impacts on the environment for different scenarios in the production stage. This method is specific to plastic products and not suitable for more general use. Li [18] identifies the product life cycle stages as making raw materials and transport methods to move them from suppliers to the factory, making the product and distributing it to customers, processing during the usage of the product, and moving the used product to a disposal site and disposal process. Due to the unavailability of data and simplification, Li [18] excludes several factors including material loss during manufacturing and raw material extraction processes, material required for maintenance, inefficiency of energy and material usage, and recycling efficiency.

While existing methods rely on system boundaries and datasets, technologies such as digital twins are emerging and offer data-driven approaches to carbon emissions assessment. A summary of selected LCA approaches and their limitations in engineering supply chains is presented in Table 1. Although LCA remains foundational in carbon emissions assessment, its application in engineering design remains limited by its data demands, static boundaries, and lack of integration with early design activities.

2.3. Eco-Indicator 99 (EI99)

EI99 is a damage-oriented method developed to simplify environmental impact assessment for product design and development. It aggregates life cycle data into a single score across three endpoint categories: human health, ecosystem quality, and resource depletion [19]. The strength of EI99 lies in its ability to translate environmental burdens into comparative damage indicators, such as disability-adjusted life years, which facilitate product ranking based on environmental impact.

Despite its intuitive scoring system, like LCA, EI99 faces limitations when applied to early design stages in engineering supply chains. First, EI99 relies on detailed product data inputs, including exact material types, process routes, and component weights, which are typically unavailable or undecided early in the design process. This makes the method better suited for design verification rather than decision-making, as it assumes stable product definitions and fixed supply chain structures. Second, the aggregation of impacts into a single environmental score introduces challenges. Trade-offs between environmental categories may be oversimplified, and design alternatives that appear favorable under one category may not be so under another. This is particularly problematic in engineering design processes that require visibility across multiple sustainability dimensions. A further limitation is the use of regionally averaged datasets, which restricts the method's applicability to global supply chains. The original EI99 framework is based on European environmental conditions and energy mixes, making its results less accurate for components sourced or manufactured in other regions, such as Asia, North America, or Africa. These regional mismatches become significant in multi-tiered supply chains where carbon emissions coefficients are different by geography.

2.4. ISO guidelines

ISO 14064 and ISO 14067 provide guidelines for the quantification and reporting of GHG emissions at the organizational and product levels, respectively [8, 20]. ISO 14064 focuses on

Table 1
LCA approaches and its limitation

Authors	Focus area	Limitations
Wang et al. [7]	Full life cycle	Requires complete product definition
Zhang et al. [12]	Electrical machines	Data-heavy manufacturing parameters
Priarone and Ingarao [13]	Metal parts via additive manufacturing	No flexibility for design change
Zhang et al. [14]	Structural components	Needs modular design input
Song et al. [15]	Carbon chain-based supply chains	Only practical with supply chain maps

emissions accounting for companies or sites [21], while ISO 14067 supports the evaluation of a product's carbon footprint based on life cycle principles [22]. These standards are implemented for environmental disclosure and are used in procurement, compliance, and marketing contexts. However, they have limitations when applied to carbon emissions assessment in engineering supply chains. First, neither ISO 14064 nor ISO 14067 highlights specific calculation methods. Instead, they offer general guidance on setting boundaries, defining functional units, and ensuring consistency and transparency. As a result, these standards are often misinterpreted as assessment methods rather than reporting frameworks. Second, the standards do not provide detailed guidance for calculating Scope 3 emissions despite their importance in engineering contexts. Scope 3 emissions represent the majority of a product's carbon footprint [9]. The standards acknowledge the need to define system boundaries, but they do not provide guidance on how to choose boundaries aligned with design decisions. This creates a challenge when engineers attempt to compare alternative design configurations or evaluate trade-offs during product development [23]. Third, ISO-based assessments typically rely on organizational reporting systems that are disconnected from iterative design workflows. In engineering supply chains, product configurations, supplier selections, and logistics strategies change frequently during the early phases. ISO standards do not accommodate such variability or support comparative design analysis under limited data conditions. As a result, while ISO 14064 and 14067 play a role in reporting carbon emissions, their lack of specificity, underrepresentation of Scope 3 emissions, and static boundary-setting approaches limit their applicability to carbon emissions assessments in the early design stages.

In summary, these two standards highlight a research gap that lies in defining system boundaries and identifying methods to quantify carbon emissions. As a result, there is a need for methods that implement ISO standard reporting structures in relation to design decision parameters, such as material choice or supplier locality, to improve the assessment of carbon emissions, especially for Scope 3 emissions.

2.5. Digital twins

Carbon emissions assessment methods, for example, LCA, often rely on predefined data and system boundaries. However, recently, digital twin technologies have emerged as an alternative approach that can improve carbon emissions assessment through real-time data integration and dynamic modeling. A digital twin is a digitized model of a real-life physical component, process, or system that provides a virtual representation for use in evaluation, testing, optimization, and simulation [24]. According to the literature, implementing digital twins to improve different aspects of manufacturing processes has become an important approach to enable different strategic visions, for example, smart manufacturing. Another paper by Azangoo et al. [25] outlined how flexible manufacturing needs systems that are adaptable to respond to different production demands. In this context, a digital twin enhances the connection between real and simulated manufacturing systems.

Shao et al. [26] describe digital twins as virtual replicas that simulate real-life processes, providing parallel digital representations of information across the life cycle of the physical system, and identify a relationship between digital twins and their real-time data collection, where digital twins are updated based on sensor data. Although Shao et al. [26] discuss the potential for digital twins to provide information for decision-making, there is no specific explanation of how this may be achieved for carbon emissions assessment. More widely, digital twins are currently used in closed-loop production systems with continuous monitoring. Their use in carbon emissions assessment is better suited to production-stage optimization than to design-stage evaluation. For early design decisions in engineering supply chains, digital twins are not yet practical because uncertainty is high, and data are limited. Their role may, therefore, be better seen as a complementary method suitable for concept evaluation. Recent studies further demonstrate that coupling digital twins with life cycle databases could be implemented for carbon emissions assessments once sufficient data are available. Nevertheless, current applications remain at the production stage [27], highlighting the research opportunity to extend digital-twin integration into conceptual design and simulation environments.

2.6. Summary

Table 2 provides a summary of carbon emissions assessment methods included in this paper. It can be seen from their strengths and weaknesses that, while several methods and standards

Table 2
Comparison of carbon emissions assessment methods

Methods	Strengths	Limitations
Life Cycle Assessment (LCA)	• Comprehensive system views • Supports cradle-to-grave assessment	• Requires detailed input data • Rigid boundaries • Low design flexibility
Eco-Indicator 99 (EI99)	• Single-score output • Intuitive damage-oriented model	• Aggregates categories • Uses European averages • Limited in supply chain variation
ISO Guidelines	• Standardized GHG reporting • widely recognized	• Lacks a calculation method • Underrepresentation of Scope 3 emissions
Digital Twins	• Real-time data integration • Support adaptive decision	• Requires sensor networks and known system parameters • Not usable during conceptual design

exist for assessing carbon emissions, their suitability for engineering supply chains remains limited, especially during early design stages. LCA and EI99 provide methodologies that are dependent on detailed data and rigid boundary definitions. ISO 14064 and ISO 14067 offer guidelines for carbon emissions reporting but fall short in providing actionable methods for engineering trade-offs and Scope 3 emissions assessment. Digital twins have potential in enabling real-time tracking of carbon emissions but are currently data-intensive and unsuitable for concept-stage modeling. Although more recent LCIA methodologies provide improvements in impact characterization, they do not resolve the challenges highlighted in this review because these methods continue to rely on complete and detailed data, which limits their applicability to early design stages, where information about suppliers, processes, and material selections is still uncertain. This further supports the need for an approach to assess carbon emissions at the early design stage, where the design data are limited.

In summary, current carbon emissions assessment methods do not sufficiently address the lack of data in early design phases, the need to address changes in supply chain configurations, the underrepresentation of Scope 3 emissions, and the iterative nature of engineering design workflows. This provides a foundation for the next section, which examines research gaps and challenges that constrain the application of current methods to early design stages.

3. Gaps and Challenges

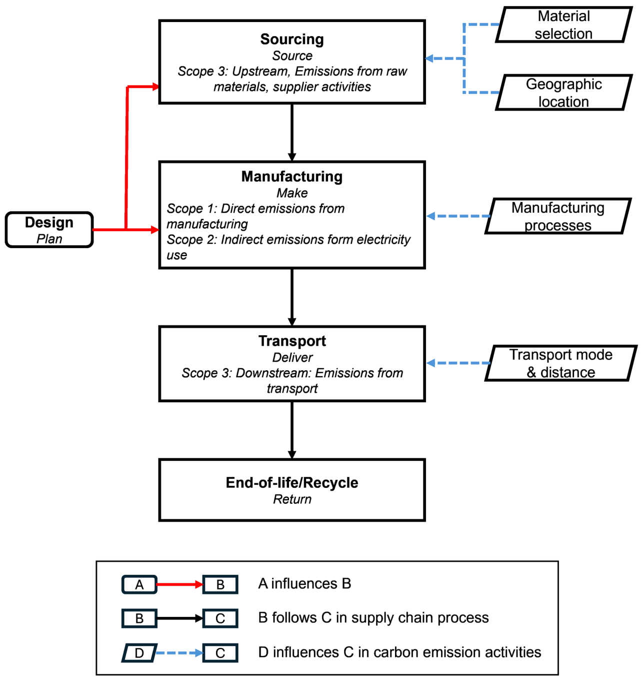
The review of current carbon emissions assessment methods reveals key limitations that hinder their application to the assessment of carbon emissions in engineering supply chains. These limitations are categorized here into three core challenges: consideration of Scope 3 emissions, use in early design processes when the scope for change is highest, and inconsistencies in boundary definitions. Together, these constrain the integration of carbon assessment within early design stages. Based on the literature review in Section 2, this section elaborates on these research gaps and provides a synthesis that links the gaps to the objectives of this review.

3.1. Underrepresentation of Scope 3 emissions

Scope 3 emissions, especially those related to raw materials, transport, and supplier manufacturing, contribute significantly to total carbon emissions in engineering supply chains [9]. However, these carbon emissions are underrepresented due to both data accessibility issues and methodological limitations in assessment methods [8, 9]. As discussed in Sections 2.2 and 2.4, existing methods such as LCA and ISO guidelines tend to focus on Scope 1 and 2 emissions, which are easier to quantify because the necessary data are available when needed. The use of these methods is rarely feasible during early design, where supplier information and logistics details are undefined. This, in turn, affects the overall carbon emissions assessment and limits the ability of engineers and decision-makers to identify carbon emission sources.

In engineering supply chains with global sourcing and multi-tier supplier structures, carbon emissions associated with transport, manufacturing processes, and global suppliers are particularly difficult to model [4]. As shown in Figure 4, the carbon emissions associated with early design decisions, such as material selection, supplier location, and transport modes, are distributed across the supply chain.

Figure 4
The influence of early design decisions on the SCOR model



Existing assessment methods often exclude these carbon emissions because supplier-specific information, such as production energy use or logistics data, is not accessible during early design. This highlights the need for methods that can be used to assess carbon emissions across distributed supply chain networks and provide early-stage feedback to support design and procurement decisions. Such methods will, necessarily, offer assumption-based estimates that reflect the influence of design trade-offs on carbon emissions beyond the design organization's direct control. Additionally, existing research and ISO standards acknowledge the importance of Scope 3 emissions but provide only limited guidance on how to assess carbon emissions at the early design stage, where data are limited. This highlights the need for frameworks that can be used to inform early design decisions and the risks they create for Scope 3 emissions that may be mitigated later in the design cycle when necessary data are more readily available.

3.2. Limitations of current carbon emissions assessment methods in early design stages

Engineering supply chains focus on product life cycles where high costs are incurred at the early design stage when knowledge of the design is limited [28]. At this stage, engineers and designers work with different design choices and supply chain configurations, where material selection, transport options, and manufacturing processes are still being explored. Consequences of decisions are difficult to assess using current carbon emissions methods that rely on complete product data and fixed design parameters [29].

As discussed in Section 2, existing methods, such as LCIA and ISO guidelines, are structured to assess product-related processes with fixed boundaries and known manufacturing parameters. EI99 and digital twins present similar challenges. EI99 relies on static scoring systems built on full product definitions

[19], while digital twins require real-time sensor data, which is unavailable in early-stage engineering [24]. These methods rely on static datasets or predefined life cycle inventories. As a result, in engineering supply chains, where designs evolve iteratively and supply chains are reconfigured across development phases, applying these methods early is unlikely to provide reliable results. The lack of input data forces engineers to rely on assumptions or to delay carbon assessment until later stages, when design change is more costly.

The problem is not only data availability but also the structure of the methods themselves. LCIA databases, for example, are based on average values and often exclude the variability introduced by design alternatives [29, 30]. ISO guidelines provide reporting structures but do not support comparative assessments between design options as they are intended for standardized reporting rather than evaluating trade-offs across design decisions. As a result, carbon emissions assessments are often disconnected from engineering workflows and are treated as separate documentation tasks rather than embedded decision methods. Furthermore, existing methods lack means of quantifying uncertainty, for example, arising from incomplete data. Early design phases require decision support tools that can adapt to design changes and different product configurations, allowing engineers and designers to evaluate how design decisions influence total carbon emissions. Introducing such uncertainty analyses would make early-stage assessments more realistic and reliable for decision-making.

3.3. Inconsistent boundary definitions

Engineering products are typically developed through multiple iterations and involve suppliers, subassemblies, and production sites distributed across different locations. Carbon emissions assessment methods such as LCIA and ISO guidelines rely on definitions of system boundaries to determine which carbon emissions are included in analyses. Common boundary types include cradle-to-gate, gate-to-gate, and cradle-to-grave (Jacquemin et al. [23]). However, for engineering supply chains, boundary-setting is difficult to standardize. This creates challenges in defining a system boundary. In practice, boundaries are adjusted based on project scope or available data, which leads to inconsistent assessment results. Additionally, design decisions during product development influence the supply chain structure, making a previously defined boundary no longer valid. For example, switching a material to reduce weight may change the supplier, transport distance, and manufacturing location, but existing assessment methods do not account for boundary shifts as a result of such decisions. On the other hand, ISO standards acknowledge the importance of boundary definitions but do not provide guidance on how to define them. For Scope 1 and 2 emissions, system boundaries can be defined based on internal operations of a given organization. However, this further contributes to the underrepresentation of upstream and downstream carbon emissions discussed earlier. The lack of structured boundary-setting approaches limits the ability of existing methods to reflect emissions in engineering supply chains. This creates gaps in carbon emissions assessment and prevents comparisons across product configurations.

Future carbon emissions assessment methods need to allow for changes according to the product design and supply chain structure. In addition, such methods need to be able to reflect changes in materials, suppliers, and transport routes as the design evolves. This adaptability can be supported through scenario analysis and simulation modeling tools that update when design changes occur. Such approaches have the potential to help ensure consistency and allow comparison between different design iterations.

In summary, the three gaps identified in this review—limited consideration of Scope 3 emissions, limited application of existing methods in early design stages, and inconsistent boundary definitions—form the basis for the requirements discussed in Section 4. These gaps highlight the barriers that need to be addressed to enable carbon emissions assessment to be integrated into engineering design workflows.

4. Requirements for Carbon Emissions Assessment Methods

The review of existing carbon emissions assessment methods highlights several limitations that reduce their suitability for engineering supply chains, especially during early design stages. Based on these limitations and insights from the literature, this section introduces requirements to guide the development of future carbon emissions assessment methods that are aligned with real-world engineering practices and sustainability goals. These requirements address the gaps discussed in Section 3 and provide guidance for the development of future methods that can operate with limited data, include Scope 3 emissions, and adapt to design and supply chain changes.

4.1. Ability to function with limited data

One of the key limitations of current methods, particularly LCA and ISO-based approaches, is their reliance on detailed product and process data, which is often not available during early design. As highlighted in the literature by Zupli et al. [5], engineering decisions made at an early stage have significant implications for the product's life cycle emissions. Future assessment methods need to be capable of assessing carbon emissions using incomplete, assumed, or estimated data. This includes offering simplified models, predefined scenarios, or data ranges that allow decision-making even when full inventories are unavailable. Additionally, these methods need to include estimation functions that allow users to test design alternatives and understand how assumptions influence total carbon emissions. This would allow engineers and designers to identify key contributors to carbon emissions early in the design process and plan mitigation strategies accordingly.

4.2. Inclusion of Scope 3 emissions

Scope 3 emissions, particularly those related to upstream activities such as raw material extraction and transport, are underrepresented in existing carbon emissions assessment methods. In engineering supply chains, these carbon emissions represent the largest share of a product's total carbon footprint. A key requirement for future methods is the ability to assess Scope 3 emissions, even when supplier-specific data are unavailable. This includes using proxy values, database averages, and carbon emissions factors that reflect geographical and process variability, while allowing transparency in assumptions. Including such transparency will help standardize results and make comparisons across supply chains more consistent.

4.3. Adaptability to supply chain structures and boundaries

Engineering supply chains are globally distributed, multi-tiered, and subject to change across development phases. System boundaries, such as cradle-to-gate and cradle-to-grave, are insufficient to capture this complexity. Carbon emissions assessment methods therefore need to offer boundary-setting flexibility, allowing users to define, adjust, and compare boundaries depending on product architecture, supplier configuration, or transport strategies [31]. This includes the ability to assess carbon emissions across sourcing, manufacturing, and delivery processes, even as supply chain structures evolve through the design process. Such adaptability would allow engineers and designers to capture how design changes influence total carbon emissions throughout the design process. Methods that include scenario-based boundary definitions also promise to help ensure comparison between design iterations.

4.4. Alignment with early design activities

While Section 4.1 addresses limited data, another key requirement is the ability to align with early design decisions. Carbon emissions assessment methods need to allow users to evaluate carbon emissions for different materials, manufacturing routes, and logistics options before final specifications are fixed. Further, these assessments need to be accessible to design engineers who may not have high levels of expertise in sustainability assessment. Key functionalities include the ability to compare multiple alternatives and to integrate sustainability considerations into existing design trade-off discussions. Integrating carbon emissions assessment into early design stages could support this alignment by enabling automatic data exchange and faster feedback for design decisions.

4.5. Consideration of engineering trade-offs

Carbon emissions are one of several criteria influencing product development decisions. Design decisions must balance cost, weight, durability, performance, and regulatory compliance. Carbon emissions assessment methods should provide carbon emissions estimations that can be used alongside other parameters in decision-making. For example, a lower emission material might introduce higher transport emissions or reduce mechanical performance. Methods are needed to allow such trade-offs to be identified and quantified to support balanced decision-making [31, 32]. In practice, this could be supported by multi-criteria decision frameworks that highlight trade-offs between environmental and engineering parameters, which, in turn, could help engineers and designers visualize how sustainability fits with other design constraints.

4.6. Structured and standardized outputs

While ISO guidelines such as ISO 14064 and 14067 offer guidance on carbon emissions reporting, they do not provide calculation methods or tool-specific outputs. Carbon emissions assessment methods should align with these standards and expand by providing clear, structured, and transparent outputs that can be traced, compared, and verified. This includes visibility into assumptions, carbon emission factors used, and boundary settings. Transparent outputs are essential for internal communication, stakeholder reporting, and compliance with industry or regulatory expectations.

Overall, these requirements summarize how future carbon emissions assessment methods can be improved to ensure sustainability is implemented across engineering supply chains at early stages of the design process. The requirements were developed from the literature review and the identified gaps and are intended to guide future research and tool development toward methods that are both holistic and practical.

5. Discussion

This paper highlights the need for methods to assess carbon emissions in engineering supply chains, especially during early design stages. In contrast to existing carbon emissions assessment methods, which are well-suited to the assessment of carbon emissions after key design decisions have been made, such methods would result in a capability to assess carbon emissions during early design stages, which typically have a significant influence on overall carbon emissions. Table 3 shows the gaps identified in the literature and the corresponding requirements proposed for carbon emissions assessment methods in engineering supply chains.

There is a need for carbon assessment methods that not only function under conditions of limited data but also adapt to the decision-making processes of product development teams. Early design stages have uncertainty and trade-offs, and existing methods are not designed to operate under these constraints. For this reason, carbon emissions methods need to be capable of integrating uncertainty analysis, for example, by using assumptions, to reflect data variability. Incorporating such features will

Table 3
Summary of methodological gaps and requirements

Identified gaps	Requirements for carbon emissions assessment methods
Underrepresentation of Scope 3 emissions	Include upstream and downstream carbon emissions, even when supplier-specific data are not available
Incompatibility with early design stages	Provide quantified outcomes using limited or assumed data during conceptual design
Inconsistent system boundary definitions	Enable flexible boundary-setting that reflects supply chain configuration and design decisions
Lack of support for early design activities	Allow carbon comparisons between materials, transport modes, and suppliers before final decisions
Lack of visibility for engineering trade-offs	Support different decision-making, allowing sustainability to be assessed alongside cost and performance
Absence of standardized outputs	Align with ISO guidelines while offering traceable carbon emissions estimates and documentation

improve the ability to assess carbon emissions at early design stages. These limitations in current methods show the need for future research focused on developing carbon assessment methods that are compatible with early design processes. Additionally, there is also a need for integration between engineering design environments, for example, computer-aided design and product life cycle management systems, and carbon emissions assessment tools to support early design decisions. The ability to compare different design decisions is essential to support decision-making in engineering supply chains. As a result, in addition to technical capabilities, further work is needed to understand how carbon emissions methods can be made more usable for engineers and designers. This is likely to involve developing user-friendly interfaces, modular assessment components, and templates that align with common product development workflows to create methods that allow engineers and designers to assess the impacts of engineering trade-offs.

While international standards provide a baseline for consistency, there remains a lack of agreement on how carbon emissions should be estimated under uncertainty or evolving system configurations. This shows a need for methods that are adaptable to help organizations to improve transparency while enabling more sustainable choices during the product development process. Aligning carbon emission assessment methods with international standards while extending their application to accommodate limited design data has the potential to bridge the gap between carbon reporting and practical design use.

Finally, this review suggests actionable recommendations for industrial applications. Engineering organizations need to consider carbon emissions in design decision-making processes by incorporating carbon emissions from material and transport selection and supplier geographical locations. Similarly, energy-related carbon emissions from manufacturing processes need to be evaluated alongside functional performance during process selection. For example, local manufacturing may reduce carbon emissions from transport but result in higher overall carbon emissions related to carbon emissions from local electricity grids.

6. Conclusion

This paper reports a critical evaluation of carbon emissions assessment methods and their applicability to engineering supply chains, specifically during the early design stage, where design decisions have a significant influence on the overall carbon emissions of a product but available data are limited. The literature search was conducted using the PRISMA approach to ensure transparent selection of sources and support reproducibility of the review. Based on existing literature, methods such as LCIA, EI99, and ISO standards are used to assess carbon emissions; however, these methods are limited in their ability to address engineering supply chains where multi-tiers and global suppliers are involved, and to support early design decisions. These limitations are evident in the underrepresentation of Scope 3 emissions, boundary definitions, and the lack of flexibility to assess carbon emissions around different design configurations. In response to these challenges, the paper proposes requirements for future carbon emissions assessment methods. These include the ability to function with limited data, support Scope 3 emissions assessment, allow flexible boundary-setting, align with early-stage design activities, enable engineering trade-offs, and produce structured outputs. The novelty of this paper lies in these requirements, defined from an engineering design perspective, so providing guidance for the development of future methods for use during early design stages. The requirements are intended to close the gap between carbon assessment practices and engineering design processes.

There is a need for holistic approaches to assess carbon emissions that can be integrated into engineering workflows. By addressing the requirements identified in this paper, future carbon emissions assessment approaches can provide quantitative outcomes for engineers and designers to assess carbon emissions data at early design stages: before the manufacturing of the product begins and when the cost of change is lowest. This, in turn, will help prevent costs incurred from design changes made after production has started. Early validation of the requirements is provided in the work of Zupli et al. [5] and Zupli [33] although further validation through simulation modeling and case studies would be beneficial to further evaluate the proposed requirements and refine the methods based on real-life situations. Future research should highlight the development and validation of such methods to align environmental sustainability goals with engineering practice in multi-tiered and global supply chain networks.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Nur Dini Binti Zupli: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Alison McKay:** Validation, Resources, Writing – review & editing, Supervision. **Richard Chittenden:** Validation, Resources, Writing – review & editing, Supervision.

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