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PESI-LCA in Building Manufacturing: A Triple-Bottom-Line Framework for Life Cycle Sustainability Assessment in the Built Environment

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Abstract: Traditional Life Cycle Assessment (LCA) emphasizes environmental impacts but often omits critical social and economic dimensions, limiting its capacity for holistic sustainability evaluation in the construction sector. This paper introduces the PESI-LCA framework (Product Environmental and Social Impact Life Cycle Assessment), which integrates environmental, social, and economic metrics into a structured, industry-ready method for comprehensive life cycle sustainability assessment. Drawing on 38 interviews across two European companies involved in building manufacturing, this study compares LCA adoption and outcomes. Company Y, applying PESI-LCA, reduced CO_2 emissions by ≈ 15%, improved energy efficiency by 10%, and achieved ≈ 8% cost savings through sustainable sourcing and process optimization. In contrast, Company X, lacking a structured LCA approach, failed to realize similar gains. The PESI-LCA framework extends LCA's utility in building manufacturing by identifying synergies across the triple bottom line and enabling alignment with emerging policy standards such as the EU Green Deal and CSRD. The findings also highlight the role of digital tools, such as AI-based tracking and supply chain analytics, as key enablers for broader PESI-LCA adoption within construction engineering contexts.

Keywords: Life Cycle Assessment; Construction Sustainability, Triple Bottom Line; Circular Economy; Building Manufacturing; PESI-LCA

1. Introduction

The building manufacturing sector plays a pivotal role in advancing global sustainability objectives, as emphasized by the United Nations Sustainable Development Goals (SDGs) and the European Union's Green Deal, particularly SDG 9, which focuses on industry, innovation, and infrastructure [1,2]. Yet, the building manufacturing sector exerts profound and interrelated impacts on the environment, economy, and society. Assessing and mitigating these impacts requires robust tools that can reflect the complexities and trade-offs involved. Traditional life cycle assessment (LCA) methodologies, primarily grounded in environmental metrics, have been instrumental in guiding sustainability evaluations but often neglect comprehensive integration of social and economic aspects

While Life Cycle Sustainability Assessment (LCSA) frameworks aim to incorporate multiple sustainability dimensions, few offer a fully structured and industry-ready methodology that effectively integrates environmental, social, and economic aspects. Existing frameworks like Social LCA (SLCA) and LCSA often lack standardized metrics and practical guidance, limiting their applicability across industries [3,4]. Environmental LCA is widely applied in manufacturing, but its traditional focus on environmental impacts overlooks critical economic and social dimensions. This study addresses the need for a more comprehensive triple-bottom-line LCA framework by proposing the Product Environmental and Social Impact Life Cycle Assessment (PESI-LCA) method [5-7]. This approach overcomes the limitations of SLCA and LCSA, which have struggled to offer concrete, actionable tools for companies [8].

PESI-LCA is especially relevant for sustainability challenges in the construction sector, where building component manufacturers, prefabrication firms, and material suppliers must comply with increasingly stringent environmental and social requirements. As the construction industry adopts off-site manufacturing and digitalized supply chains, integrated LCA tools are needed to align production decisions with frameworks such as the EU Green Deal and the UN Sustainable Development Goals [1,2]. By incorporating metrics that reflect labor conditions, lifecycle costs, and supply chain ethics, PESI-LCA enables construction-sector firms to move beyond environmental assessments and implement a triple-bottom-line approach to decision-making. In doing so, the framework supports regulatory compliance and strategic sustainability efforts within the construction value chain [5-7].

Despite advances in LCA, many building manufacturing companies still prioritize economic performance over social and environmental considerations, which undermines broader sustainability objectives [9]. However, industries are increasingly adopting comprehensive sustainability practices, with sectors like automotive and electronics setting ambitious net-zero and circular economy targets. PESI-LCA provides a scalable solution for companies to track and improve sustainability performance across environmental, social, and economic dimensions.

Conventional LCA methodologies often depend on generic life-cycle inventories and standardized assumptions, potentially overlooking critical contextual and site-specific impacts. To address this, PESI-LCA incorporates locally relevant social and economic metrics (in addition to environmental data), enabling a more accurate assessment of each company's unique sustainability profile [7,10]. By offering a cohesive, actionable methodology, PESI-LCA facilitates the integration of all three sustainability dimensions into manufacturing decision-making, advancing both theoretical and practical sustainability efforts.

This paper advances the literature on sustainability transitions by operationalizing triple-bottom-line assessment through a novel, systems-based framework that has been empirically validated in practice. The PESI-LCA supports socio-technical transition strategies by linking industrial decision-making with global environmental and social outcomes, thereby aligning with Sustainability Science's mission.

Research Objectives

To address the identified gap, we address these research questions:

- RQ1. How can environmental and social impacts be jointly assessed in manufacturing LCA?
- RQ2. How do results differ between case companies under PESI-LCA?
- RQ3. What empirical evidence supports the practical implementation and effectiveness of the PESI-LCA framework?

Bridging this gap not only enhances the applicability of LCA but also aligns with global sustainability goals, including the UN SDGs. The adoption of integrative frameworks such as PESI-LCA can drive innovation, inform policy, and promote sustainable practices across industries [7].

2. Literature Review

2.1 Life Cycle Assessment

LCA has emerged as a pivotal methodological framework for evaluating the environmental impacts associated with products, services, or processes across their entire lifecycle. The PESI-LCA framework builds on multiple theoretical perspectives. The Triple Bottom Line [11] underscores the need for balancing economic, social, and environmental concerns in corporate sustainability. Circular Economy [12] emphasizes resource efficiency, which PESI-LCA incorporates through modular design and closed-loop manufacturing. Industrial Ecology [13] highlights the systemic interconnections between industrial processes, guiding the integration of social and economic factors into LCA.

PESI-LCA synthesizes key sustainability theories into a comprehensive framework that extends standard LCA by embedding social and economic metrics into each phase [14]. The research framework builds on standard LCA methodology (goal and scope definition, inventory, impact assessment, interpretation) but extends it by integrating social and economic metrics (**Figure 1** illustrates these phases and where PESI-LCA adds new indicators). This development follows Backes et al. [7] comments to broaden LCA's scope.

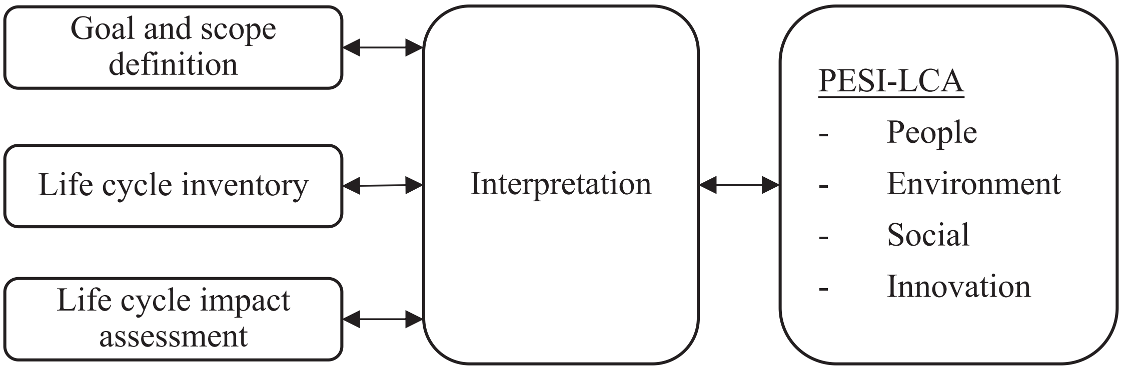

Figure 1. PESI-LCA enhanced the standard LCA phases.

Despite its widespread adoption, LCA has faced critiques regarding data reliability and methodological consistency. Standardized datasets, while essential for comparability, can obscure regional and contextual variations, limiting the precision of the analysis [15]. Moreover, LCA has historically focused on environmental impacts, often neglecting the intertwined social and economic dimensions of sustainability. This narrow scope has underscored the need for integrative frameworks that capture the full spectrum of impacts associated with products and processes.

2.2 PESI-LCA Framework

Recognizing the limitations of traditional LCA, researchers have proposed the PESI-LCA framework as a more inclusive methodology. PESI-LCA extends the analytical scope by incorporating social and economic considerations alongside environmental impacts, thereby addressing the triple bottom line of sustainability [6]. This framework seeks to operationalize the interconnected dimensions of sustainability by integrating indicators such as labour rights, community well-being, and equitable resource distribution.

The theoretical foundation of PESI-LCA is rooted in its holistic approach, which aligns closely with the principles of sustainable development. While SLCA has significantly contributed to identifying social impacts, challenges remain in quantifying these effects consistently and reliably across different industries [3,15]. Recent developments, such as ISO 14075 [16], offer guidance on integrating social indicators into LCA; however, practical applications remain limited [3]. PESI-LCA addresses this gap by offering a multidimensional framework that supports more informed decision-making. Nevertheless, implementing PESI-LCA in practice remains complex, largely due to the limited availability of robust data on social indicators [15]. Social indicators frequently rely on qualitative assessments, which can introduce subjectivity and variability into the analysis. Consequently, efforts to standardize data collection and enhance the reliability of these indicators are critical for advancing the practical application of PESI-LCA [7]. PESI-LCA acts as an operational bridge between Industrial Ecology (systems-level optimization), Circular Economy (resource loops), and Triple Bottom Line (value distribution), translating these principles into measurable LCA practices. As shown in **Figure 2**, PESI-LCA positions LCA within a broader sustainability theory context.

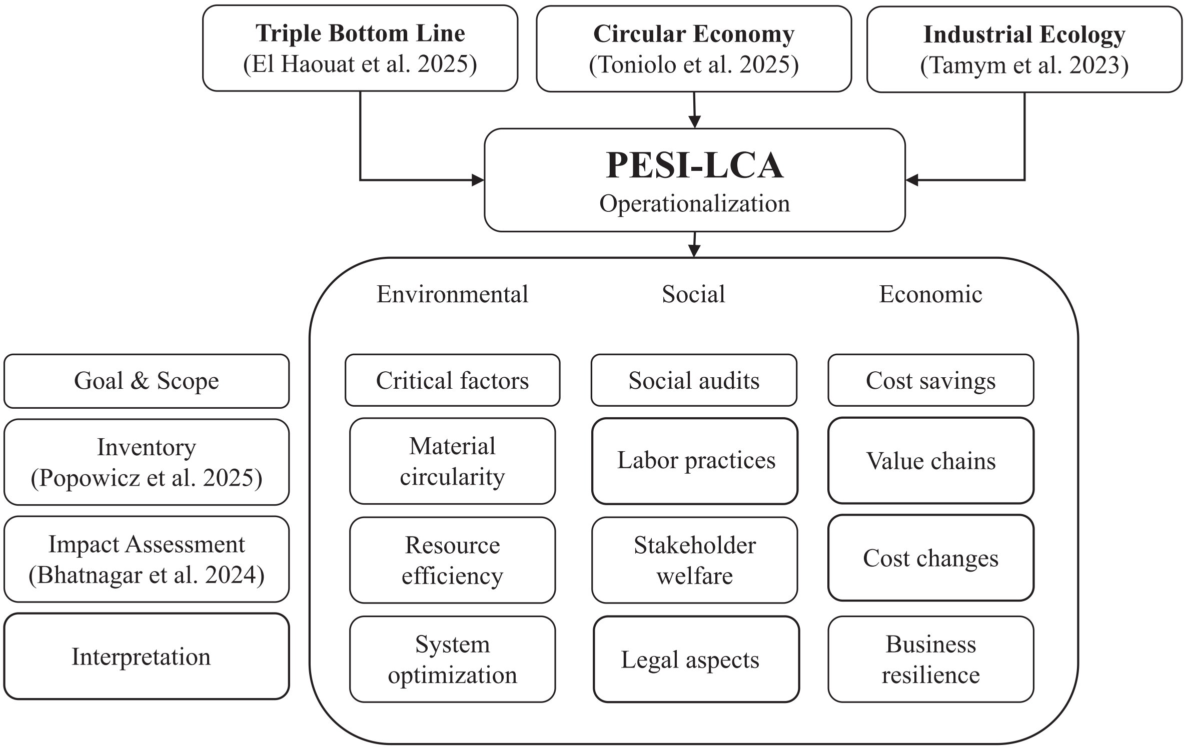

Figure 2. PESI-LCA framework as an extension of ISO LCA and sustainability theory.

While the Triple Bottom Line [17], Circular Economy [12], and Industrial Ecology [13] provide foundational sustainability frameworks, their application in life cycle assessments often remains high-level or conceptual. PESI-LCA extends these theories by operationalizing them through the established ISO 14040/14044 [16] LCA structure.

Rather than introducing a new sustainability paradigm, PESI-LCA acts as a practical instantiation of Life Cycle Sustainability Assessment (LCSA), integrating measurable environmental, social, and economic indicators into each LCA stage (goal definition, inventory, impact assessment, and interpretation). This makes PESI-LCA a methodological bridge, translating normative principles into actionable and quantifiable metrics that enable systematic sustainability analysis across product life cycles.

PESI-LCA builds upon the four conventional LCA phases—goal and scope definition, inventory analysis, impact assessment, and interpretation—by systematically incorporating social indicators (e.g., labor rights, community well-being) and economic metrics (e.g., life-cycle costs) into each phase. **Table 1** illustrates examples of these additional metrics across the LCA stages, enabling decision-makers to identify sustainability trade-offs and opportunities in alignment with the triple bottom line.

Table 1. Bridging the Theoretical Gap with the PESI-LCA Framework

Framework	Strengths	Weaknesses	Challenges
LCA	Well-established, widely used	Focuses only on environmental aspects	Ignores social and economic dimensions
SLCA	Incorporates social sustainability	Lack of data standardization, subjective indicators	Difficult to integrate into traditional LCA
ES-LCA	Attempts to integrate environmental and social impacts	Complex methodology, difficult to apply in industries	No clear guidelines for economic assessment
PESI-LCA	Integrates environmental, social, and economic dimensions	New framework, needs empirical validation	Provides a structured approach for holistic LCA implementation

In practice, PESI-LCA involves adding social impact indicators (e.g., labor rights, community well-being) and economic performance metrics (e.g., life cycle cost analysis or cost savings from sustainability initiatives) into each phase of LCA (goal and scope, inventory, impact assessment, interpretation). PESI-LCA supports compliance with global sustainability mandates, notably the UN SDGs [1] and EU Green Deal [2]. Leveraging AI-driven analytics, digital supply chain tracking, and policy incentives can mitigate these challenges, making PESI-LCA a practical tool for sustainable manufacturing [18,19].

To enhance the operationalization of the social dimension, PESI-LCA draws on established guidelines such as the UNEP Guidelines for Social Life Cycle Assessment [20] and the Global Reporting Initiative [21]. Indicators may include: fair wage ratios, health and safety incident rates, training hours per employee, gender equity in leadership roles, and supplier human rights audits [3, 21]. These metrics can be integrated in the inventory and impact assessment phases to provide a robust social footprint.

2.3 Sustainability in Manufacturing: Triple Bottom Line

The triple bottom line (TBL) framework—comprising environmental, social, and economic dimensions—offers a holistic lens on sustainability [16,22]. It emphasizes ecological preservation, social equity, and financial viability as interdependent goals [23]. TBL highlights the connection between these dimensions, advocating for strategies that balance competing priorities. For example, implementing circular economy principles can simultaneously reduce environmental impacts, create economic value, and promote social equity. Logistics and supply chain operations are crucial to this balance, as their efficiency and sustainability directly influence the environmental and economic dimensions of the TBL. Technologies such as blockchain for transparent sourcing, IoT for supply chain visibility, and leveraging AI-driven analytics and digital tracking can make PESI-LCA practical contributing to achieving sustainable supply chains [8,9,24,25].

The PESI-LCA framework builds on the Triple Bottom Line (TBL) theory, which emphasizes balancing environmental, social, and economic impacts in sustainability efforts [23]. It also integrates Circular Economy principles [12] to promote resource efficiency, alongside Industrial Ecology's focus on systemic interconnections [13].

2.4 Limitations of Current LCA Models

While LCA provides a robust framework for assessing environmental impacts, advancing LCA requires the development of standardized datasets for social indicators, cross-disciplinary collaboration, and the integration of qualitative and quantitative methods [8]. Logistics and supply chain considerations are integral to bridging this gap, as they influence the efficiency and sustainability of every stage of the product lifecycle. Innovations in green logistics, such as the use of electric or hydrogen-powered vehicles and the optimization of reverse logistics for recycling, are critical for addressing the environmental and economic dimensions of sustainability [26].

3. Methodology

3.1 Research Design and Case Selection

We conducted a comparative multiple-case study [27] with a mixed-methods approach (semi-structured interviews and secondary data) to examine LCA implementation in two European building manufacturing companies in the building sector. Semi-structured interviews were used to capture nuanced perspectives, while secondary data from reports and industry standards triangulated findings to ensure reliability. Data analysis employed thematic coding [28], supported by content analysis to quantify key themes. This mixed-method approach enhances credibility of findings. The empirical case studies further validate its applicability, offering valuable insights for both researchers and practitioners.

The study was structured using a benchmarking framework, encompassing five stages: (1) Defining case companies and study scope; (2) Collecting empirical and secondary data; (3) Analyzing data to identify patterns, gaps, and strengths; (4) Proposing methodological improvements tailored to each company; (5) Disseminating findings and recommendations. The benchmarking process followed guidelines suggested by Bryman and Bell [29] and Soh et al. [30], emphasizing comparative analysis to generate practical and theoretical insights.

The selected companies operate in the same industry and region, making their sustainability performance broadly comparable. Company X and Company Y were selected for their contrasting approaches to sustainability, representing companies at different stages of LCA adoption. While Company X represents companies struggling with sustainability integration, Company Y exemplifies best practices in structured LCA implementation. This contrast allows for an in-depth exploration of the challenges and success factors associated with LCA adoption in different organizational contexts. Although the case study is limited in scope, it provides valuable insights into the challenges and benefits of adopting PESI-LCA that may be transferable to similar manufacturing companies within industrialized economies [27]. To ensure validity, a triangulation approach combined semi-structured interviews, organizational reports, and benchmarking against industry standards. Discrepancies in interview data were resolved through respondent validation and cross-referencing with secondary sources [29].

3.2 Data Collection

A purposive sampling strategy was employed to ensure that the respondents had relevant expertise and decision-making authority to contribute meaningfully to the study. A total of 38 in-depth interviews were conducted. The interviewees were identified via purposive sampling using role-based selection (e.g., sustainability officer, supply chain lead), ensuring coverage of strategic and operational viewpoints. The sample includes leadership and operational roles in both companies.

Semi-structured interviews served as the primary data collection tool, and interviews were conducted using an interview guide designed around the study's thematic areas, including operational practices, strategic decision-making, and sustainability considerations. This format provided the flexibility to probe individual perspectives while maintaining comparability across both case studies [29].

In addition to the interviews, secondary data were collected from Company X and Y's sustainability reports, process manuals, and industry guidelines. These documents were analyzed to supplement interview findings and ensure data triangulation. We also consulted external sources, including industry-specific guidelines, regulatory frameworks, and academic literature. Key references such as the ISO 14040/14044 [16] standards for LCA and relevant European Commission sustainability reports were reviewed to benchmark the companies' practices against established norms [2,14,16]. Furthermore, an extensive literature search was performed identifying common metrics and challenges in implementing LCA. Together, these multiple data sources provided a robust evidence base for understanding each case and enabled cross-verification of information (data triangulation).

3.3 Data Analysis

We used a combination of qualitative thematic analysis and quantitative content analysis to examine the collected data. Interview transcripts were thematically coded [28]. Coding was conducted inductively, with initial categories based on key research themes (e.g., sustainability challenges, economic performance, social impact). To ensure consistency and reliability, two researchers independently coded the data, and discrepancies were resolved through discussion. This involved open coding of interview transcripts to identify recurring themes in how LCA was understood and practiced, such as methodological gaps in the current LCA approach, environmental impact focus areas, and inclusion (or lack) of social sustainability considerations. Codes were iteratively refined and grouped into broader themes that characterize each company's LCA implementation profile.

Content analysis quantified recurring themes (e.g., compliance, cost, training), enabling systematic comparison between companies, e.g. we counted how often participants mentioned factors like regulatory compliance, cost constraints, or employee training in the context of LCA. This mixed analytic approach allowed for systematic cross-case comparison: we could not only qualitatively describe differences between Company X and Company Y, but also gauge the relative emphasis each company placed on various sustainability dimensions. By integrating qualitative and quantitative analyses, we strengthened the rigor of our interpretations—ensuring that patterns identified in narrative data were supported by quantitative trends—and gained a nuanced understanding of each case's strengths and weaknesses in LCA practice [6,7,10].

3.4 Validity and Reliability

The combination of qualitative (interviews) and quantitative/archival data allows us to triangulate findings and enhance validity:

● Triangulation: We corroborated information by comparing multiple data sources, combining the interview findings with organizational documents and literature. Consistent patterns observed across independent sources increased confidence in the results [31].

● Respondent validation: Interview participants were given the opportunity to review and confirm the accuracy of their transcript excerpts and our interpretations of their input [29].

● Standardized protocols: We used a consistent interview guide and data collection procedure across both cases to ensure uniformity. All interviews covered the same key topics, and coding was conducted with a predefined framework.

By adhering to these strategies, the study minimized potential biases and increased the credibility of its results. In particular, triangulating qualitative and secondary data and, where feasible, involving participants in validating findings helped to ensure that conclusions drawn were trustworthy and grounded in the evidence [27].

3.5 Limitations

Despite the robust design of this study, certain limitations must be acknowledged. First, focusing on only two case companies inherently limits the generalizability of the findings. While the two case companies operate in similar building manufacturing sectors, differences in market positioning and resource availability may also influence outcomes. Future research should expand the sample size to confirm generalizability. The experiences of Company X and Company Y, while illustrative, may not represent the full spectrum of LCA practices across the entire manufacturing sector. Second, the study's reliance on qualitative methods (interviews and case analysis) introduces a degree of subjectivity into the findings. Individual biases and perceptions could influence the information provided by participants and its interpretation. We attempted to mitigate this through triangulation of data sources and clear analytical protocols, but some subjectivity remains.

4. Results: Case Studies

The findings reveal differences in their approaches to LCA implementation and the challenges they face. The analysis draws on theoretical perspectives and previous research, including studies by Bouillass et al [15], Busch [10], Schramm et al. [6] and Backes et al [7], to contextualize the practical implications of LCA adoption in the building manufacturing industry.

4.1 Current LCA Implementation and Challenges (RQ1)

Company X's LCA Practice: Company X lacks a clear LCA methodology. Management's focus on immediate cost efficiency means that sustainability efforts are often deprioritized. A Supply Chain Manager at Company X admitted *"We are yet to implement an LCA process systematically. The lack of a clear methodology has been a barrier,"* (Respondent 7). Additionally, a senior manager noted that short-term economic pressures override sustainability initiatives, echoing the pattern that many companies prioritize cost over environmental and social goals [9]. This demonstrates a key challenge: without a structured framework, integrating social and economic dimensions into LCA is difficult, as there is little guidance or incentive beyond compliance. Company X's case highlights common hurdles identified in literature – lack of expertise, fragmented data, and an organizational culture focused on short-term financial performance [9,15].

Company Y's Current LCA Practice: In contrast, Company Y has implemented a structured LCA approach aligned with the PESI-LCA framework. With the help of environmental consultants, Company Y embedded LCA into its core operations. The Sustainability Manager of Company Y explained that collaborating with external experts *"allowed us to establish a structured approach to evaluate our products' environmental impact systematically,"* (Respondent 3). This structured methodology enables Company Y to incorporate broader sustainability metrics. For example, Company Y systematically tracks environmental impacts across product life cycles and conducts regular reviews of social and economic performance indicators. The case of Company Y shows that with dedicated resources and expertise, a company can overcome initial knowledge gaps [10] and integrate LCA into decision-making. Importantly, even Company Y – despite its advanced approach – encountered challenges in fully integrating social and economic dimensions (e.g., developing consistent social impact measures), which is a known difficulty in LCA expansion [7].

Key Insight (RQ1): Company X's fragmented, environment-only focus versus Company Y's structured PESI-LCA approach illustrates the current state of LCA practice. The main challenges hindering integration of social and economic factors include lack of clear methodology, limited data for social impacts, and a corporate emphasis on short-term economic gains. These findings underscore the need for a structured framework (like PESI-LCA) to guide companies beyond environmental metrics.

4.2 Enhancing LCA with PESI-LCA (RQ2)

Environmental Dimension: With PESI-LCA, Company Y achieved a more thorough environmental assessment and better environmental outcomes. It invested in cleaner technologies and process optimizations that reduced its environmental footprint. Over three years, Company Y's PESI-LCA-driven efforts yielded a ≈ 15% CO_2 reduction and a 10% gain in energy efficiency (Company Y internal report). Additionally, by redesigning products for disassembly and implementing recycling initiatives, Company Y cut waste generation by 40%. These proactive measures go beyond what a conventional LCA might prompt. Company X, lacking PESI-LCA, did not systematically pursue such improvements. It has no formal emission tracking mechanism, leading to high variability in sustainability data and missed opportunities for emission reduction. Moreover, Company X faces difficulties in managing supply chain emissions (relying on third-party logistics without clear oversight), reflecting how an unstructured approach struggles to address complex environmental impacts. In summary, PESI-LCA enhances the environmental scope of LCA by pinpointing areas for emission reduction, energy savings, and waste minimization that a traditional approach might overlook.

Social Dimension: PESI-LCA also broadens the social scope of LCA. Company X has no Social LCA component and thus overlooks social impacts such as worker welfare, community effects, and ethical sourcing. In contrast, Company Y extended its assessment to include social criteria: it integrated SLCA principles by conducting supplier audits and implementing employee welfare programs. Over 60% (as of 2024) of Company Y's suppliers now meet stringent environmental and social criteria (Respondent 5), ensuring ethical labor practices and community standards in the supply chain. These efforts illustrate how PESI-LCA makes LCA more applicable to real-world sustainability goals by addressing stakeholder interests and social risks. However, the case studies also reveal that integrating social factors remains challenging – even Company Y's approach is only a starting point (focused on audits and compliance). Both companies lack comprehensive quantification of social impacts, highlighting the need for standardized social impact metrics and guidelines [7,22]. In effect, PESI-LCA provides a structure to include social considerations, but industries need further development of tools and data to fully realize this dimension.

Economic Dimension: Incorporating economic sustainability into LCA ensures that long-term financial implications of environmental and social actions are evaluated. Company X's traditional LCA approach paid little attention to long-term economic sustainability – its decisions were driven by immediate costs, leading to supply chain inefficiencies (e.g., 5–10% higher raw material costs due to unsustainable sourcing) and increased compliance costs from poor ESG alignment. In contrast, Company Y's PESI-LCA approach treats sustainability as an investment: by pursuing energy efficiency and sustainable sourcing, it achieved 8% cost savings in materials and operations. Company Y's Technical Manager noted that *"long-term investment in LCA has not only improved our environmental impact but has also contributed to operational efficiency,"* affirming that sustainable practices can reduce costs over time. Thus, PESI-LCA enhances LCA's applicability by linking sustainability initiatives to economic performance – it helps companies identify cost-saving opportunities (through waste reduction, energy savings, and risk mitigation) that might be overlooked if only short-term costs were considered. This comprehensive view supports the triple bottom line approach, aligning environmental and social initiatives with economic benefits.

Key Insight (RQ2): The PESI-LCA framework makes LCA more comprehensive and actionable. Company Y's case shows that a structured PESI-LCA approach encourages improvements across all sustainability pillars: environmental (emissions, energy, waste), social (labor and community considerations), and economic (cost efficiency and risk reduction). By contrast, Company X's unstructured approach leads to gaps in each area. The enhancement comes from

PESI-LCA's ability to integrate these dimensions into the decision-making process, thereby extending the usefulness of LCA from a narrow environmental audit to a holistic sustainability tool.

4.3 Empirical Validation of PESI-LCA (RQ3)

Company Y's Outcomes (With PESI-LCA): Over the study period, Company Y realized sustainability gains: CO_2 emissions were reduced by ≈ 15%, energy efficiency improved by 10%, and waste generation dropped by 40% (due to recycling and circular design). Economically, these sustainability efforts translated into an 8% cost savings through sustainable material sourcing and process efficiencies. Socially, while harder to quantify, Company Y improved supplier compliance with social standards and invested in employee well-being programs, which likely enhanced its reputation and stakeholder relationships. These outcomes demonstrate that PESI-LCA is not just a theoretical concept but a practical framework that leads to measurable improvements in environmental performance, cost reduction, and progress on social responsibility. The success of Company Y in multiple dimensions validates PESI-LCA's premise that integrating the triple bottom line into LCA supports sustainable manufacturing.

Company X's Outcomes (Without a Structured LCA): Company X, which did not implement PESI-LCA, experienced comparatively poor sustainability performance. The company struggled with inconsistent data and unchecked emissions. It also incurred higher operational costs – for example, 5–10% higher raw material expenses due to inefficiencies in its supply chain and missed opportunities for sustainable sourcing. Additionally, by neglecting formal social and environmental programs, Company X faced increased regulatory and compliance risks (and costs) as global ESG standards became stricter. The shortcomings observed at Company X serve as a counterfactual: they underscore what can happen in the absence of an integrated sustainability framework. Essentially, Company X's case reinforces the notion that traditional LCA, when applied in a piecemeal or purely environmental manner, fails to capture crucial sustainability benefits and can even lead to higher long-term costs.

Key Insight (RQ3): Company Y's gains across all TBL metrics validate PESI-LCA's practical benefits. Company X's struggles reaffirm the limitations of conventional, environmentally narrow LCA approaches. Together, these case findings answer RQ3 by showing that PESI-LCA is both practically implementable and beneficial: it helps achieve regulatory compliance, operational efficiencies, and sustainable development goals. In contrast, an unstructured approach falls short in all these areas. **Table 2** below summarizes the key differences between the companies, highlighting the impact of an unstructured versus structured LCA implementation.

Table 2. Key differences between Company X and Company Y (unstructured LCA vs. PESI-LCA)

Sustainability Dimension	Company X (Unstructured LCA)	Company Y (Structured PESI-LCA)
Environmental Performance	- **Emissions:** No formal tracking of CO_2 emissions; unable to demonstrate reductions.	- **Emissions:** Achieved ≈ **15% reduction** in CO_2 emissions through systematic LCA-driven improvements.
	- **Energy Use:** Limited energy optimization, leading to stagnant efficiency.	- **Energy Use:** Implemented process optimizations and green tech, yielding **10% increase** in energy efficiency.
	- **Waste Management:** Traditional linear processes, contributing to higher waste (no circular initiatives).	- **Waste Management:** Adopted circular economy practices (recycling, design for disassembly) cutting waste generation by **40%**.
Social Performance	- **SLCA Integration: Absent** – no formal Social LCA or social impact tracking in place.	- **SLCA Integration: Present** – incorporated social criteria via supplier audits and employee welfare programs.
	- **Labor & Community:** Reactive compliance only; potential issues in supplier labor practices due to lack of audits.	- **Labor & Community:** Ensures ethical sourcing (over 60% of suppliers meet strict social standards) and invests in worker well-being, improving community relations.
	- **Stakeholder Engagement:** Limited transparency, leading to higher ESG compliance risk.	- **Stakeholder Engagement:** Greater transparency and accountability, reducing risk and improving brand trust.

Continuation Table:

Sustainability Dimension	Company X (Unstructured LCA)	Company Y (Structured PESI-LCA)
Economic Performance	- **Cost Implications:** Short-term cost focus; **5–10% higher** raw material costs due to inefficient, non-sustainable sourcing. - **Compliance Costs:** Higher long-term costs from ESG non-compliance (penalties, lost opportunities). - **Strategic Outlook:** Views LCA as a cost burden, resulting in missed efficiency gains.	- **Cost Implications:** Long-term sustainability investments yield **8% cost savings** (cheaper materials via sustainable sourcing, energy savings). - **Compliance Costs:** Lower risk of fines/non-compliance by meeting environmental and social regulations proactively. - **Strategic Outlook:** Treats LCA as an investment; gains competitive advantage and operational efficiencies over time.

5. Discussion

The discussion is organized around the three research questions (RQ) to compare our case findings with existing literature, interpreting how the evidence either validates or challenges current LCA methodologies.

5.1 LCA Implementation and Challenges (RQ1)

The comparative analysis of Company X and Company Y highlights disparities in LCA implementation, consistent with patterns observed in prior research. Company X's reactive, cost-driven approach exemplifies the challenges many companies face in broadening LCA adoption. Its LCA practice remains ad hoc and primarily focused on environmental impacts, which corroborates findings by Paryathy et al. [9] that manufacturers often prioritize short-term financial performance over sustainability goals. Similarly, Trollman et al. [22] suggest that perceived financial burdens lead companies to sideline comprehensive sustainability initiatives, a trend evident at Company X.

In contrast, Company Y's proactive and structured LCA approach demonstrates how embedding LCA into strategic planning can lead to more effective adoption. The engagement of external consultants and dedicated sustainability staff supports Busch's [10] suggestion that external expertise is crucial to overcoming internal knowledge gaps in LCA implementation. This finding further extends Schramm et al.'s [6] argument, empirically showing that collaboration with external experts can enhance LCA integration, as evidenced by Company Y's success.

The contrast between Company X and Company Y reinforces a key point from the literature: effective LCA implementation requires sustainability to be embedded into core business strategy, rather than treated as a peripheral concern. Company Y incorporated LCA into its operations by involving top management and cross-functional teams, whereas Company X viewed it as an add-on constrained by cost concerns. This difference in approach led to markedly different outcomes, supporting Backes et al.'s [7] argument that LCA implementation success correlates with its integration into decision-making processes. Thus, our discussion of RQ1 confirms that current LCA practices are uneven across companies. The challenges identified at Company X—such as lack of methodology, cost focus, and limited social data—mirror those found in the literature. On the other hand, Company Y's case illustrates how these challenges can be mitigated through a structured approach. Our findings validate the limitations of traditional LCA methodologies while demonstrating that adopting a comprehensive framework, like PESI-LCA, can address these shortcomings.

5.2 Enhancing LCA with PESI-LCA (RQ2)

Findings confirm that PESI-LCA strengthens traditional LCA by embedding all three sustainability dimensions into practice. Below, we discuss the key enhancements in each dimension:

Environmental Enhancement: Company Y's implementation of PESI-LCA resulted in measurable environmental improvements, including reduced emissions, energy savings, and waste reduction. This outcome aligns with the lifecycle thinking central to sustainable manufacturing. By considering environmental impacts at every stage—from raw material sourcing to end-of-life—Company Y's approach is consistent with the principles of sustainable product design and circular economy [4,32]. In contrast, Company X's challenges with tracking environmental impacts, particularly from third-party logistics, highlight common issues in traditional LCA practice, such as difficulties managing supply chain emissions [18,33].

Furthermore, Company X's lack of detailed production impact data mirrors the limitations identified by Busch [10], who argue that without context-specific data, companies cannot identify inefficiencies. Company Y's success in utilizing data and technology—such as high-tech solutions for energy efficiency—demonstrates how PESI-LCA's structured approach can overcome these barriers, supporting Schramm et al. [6] that collaboration and digital tools improve LCA effectiveness [19].

Social Enhancement: Incorporating social factors into LCA remains a challenge, but Company Y's partial success in this area demonstrates how PESI-LCA can improve social accountability. Both companies struggled to integrate social considerations, as expected [7,15] due to the lack of standardized metrics for social impacts. Company X did not incorporate any social factors, which is typical in industries where companies focus primarily on environmental metrics [23]. In contrast, Company Y took steps to integrate social criteria, such as labor practices and employee welfare, aligning with the growing trend towards ethical sourcing and corporate social responsibility [6]. This suggests that PESI-LCA can enhance the social dimension of LCA by providing a framework for incorporating qualitative social measures.

Despite this, our findings also highlight the ongoing limitations of current LCA methodologies. Even with PESI-LCA, fully capturing social sustainability remains difficult. Company Y's reliance on qualitative audits rather than quantitative metrics underscores the need for further methodological advancements in Social LCA [15]. These challenges reflect the broader literature's call for improved SLCA tools and standardized social impact metrics [22], highlighting an area for future development in LCA practices.

Economic Enhancement: The cases illustrate how PESI-LCA aligns sustainability efforts with economic performance. Company X's focus on short-term cost-cutting aligns with the literature's assertion that many companies hesitate to invest in sustainability without immediate financial returns [9]. This short-term perspective often leads to missed long-term gains, as seen in Company X's inefficiencies and increased compliance costs. In contrast, Company Y's approach demonstrates that integrating economic factors into LCA can lead to long-term financial benefits. By evaluating the economic impact of environmental and social initiatives, a core element of PESI-LCA, Company Y was able to justify investments in energy efficiency and sustainable materials, resulting in cost savings and enhanced competitiveness. This finding aligns with Padilla-Rivera et al. [8], who argue that sustainability and profitability are mutually reinforcing when considered holistically, and with [6] who suggest that strategic sustainability initiatives can drive operational efficiencies. Our discussion confirms that PESI-LCA makes LCA more relevant to business strategy by highlighting the economic benefits of sustainability measures—an aspect that traditional LCA often overlooks. The evidence from Company Y validates the idea that a triple-bottom-line approach can foster cost efficiency and innovation, challenging the misconception that sustainability is purely a cost center.

These insights are particularly relevant for construction engineering, where sustainability strategies increasingly rely on data-driven life cycle analysis of materials and processes. Construction firms, especially those engaged in off-site manufacturing or modular systems, can apply PESI-LCA to evaluate environmental footprints, ensure labor and supply chain compliance, and quantify lifecycle costs. This expands the utility of LCA from environmental accounting to an integrated tool supporting procurement, design, and risk management in the built environment. Beyond manufacturing, PESI-LCA offers a prototype for sustainability governance frameworks across sectors, particularly under the EU's Corporate Sustainability Reporting Directive and ISO 14075 standards. Its scalability, however, hinges on digital infrastructure and cross-sector coordination, critical bottlenecks in many transition pathways.

In summary, PESI-LCA broadens the scope of LCA by integrating environmental, social, and economic dimensions. Our case study comparisons show that PESI-LCA's structured approach can yield improvements across all three areas. While PESI-LCA strengthens LCA's applicability, our findings also underscore existing gaps, particularly in social impact measurement, pointing to a need for further advancements in the methodology.

5.3 Empirical Support for PESI-LCA (RQ3)

The results from Company X and Company Y provide valuable insights into the practical application of

PESI-LCA and its alignment with existing LCA methodologies. Our empirical evidence strongly supports the effectiveness of integrated LCA. Company Y's sustainability improvements validate literature claims that structured LCA enhances outcomes [6]. In fact, our study offers real-world confirmation of theoretical arguments that adopting a comprehensive sustainability framework like PESI-LCA leads not only to better environmental performance but also to economic and strategic benefits. This marks a critical shift from theoretical discussions to practical application.

Our findings also support critiques of traditional LCA. Company X's limitations reflect the shortcomings highlighted by Bouillass et al. [15] and Busch [10]: conventional LCA methodologies, which focus primarily on environmental impacts, fail to adequately address social and economic factors. Company X's struggles with fragmented data, absence of social assessments, and missed economic opportunities empirically challenge the adequacy of current LCA practices. These issues reinforce the literature's call for LCA to evolve to incorporate the triple bottom line [22]. Thus, Company X's experience serves as a cautionary tale, reinforcing the need for more comprehensive frameworks like PESI-LCA.

When comparing the two cases, we find that Company Y's success aligns with optimistic perspectives on sustainable innovation, while Company X's difficulties are consistent with the documented barriers to LCA implementation. Company Y's example shows that with commitment and a structured approach, the theoretical benefits of integrated LCA can be realized, supporting the discussions by Seuring and Müller [31], who argued that sustainability integration can improve decision-making and performance. Additionally, the fact that Company Y relied on external expertise and digital tools underscores the importance of collaboration and innovation in successful LCA implementation, in line with Schramm et al. [6] and Setyadi et al. [26].

Across all three research questions, our case comparisons validate existing literature on life cycle sustainability assessment and move the conversation forward. Our findings confirm known challenges, such as integrating social aspects, while demonstrating that solutions proposed in the literature, such as collaboration, long-term perspectives, and LCA integration into strategy, yield positive results in practice. This study challenges the status quo of LCA by showing that businesses can, and should, expand their LCA approach to embrace all three dimensions of sustainability if they are to achieve true sustainability in manufacturing.

Our proposed PESI-LCA framework operationalizes the triple bottom line in a manner that previous LCSA models have not, providing a step-by-step methodology with standardized indicators and emphasizing practical adoption in alignment with policy requirements (e.g., EU Green Deal). This structured approach offers a novel contribution by moving beyond theoretical sustainability assessment to provide a concrete, implementable tool for industry.

6. Conclusion

This study demonstrates that the PESI-LCA framework offers a viable and effective enhancement to conventional LCA by enabling integrated sustainability assessments. Through case-based evidence, we show that triple-bottom-line assessments are not only conceptually sound but also practically achievable and beneficial for building manufacturing firms.

The contrasting experiences of Company X and Company Y illustrate the critical importance of methodological structure. Company X's challenges, including fragmented data, a narrow environmental focus, and cost-driven decision-making, are consistent with barriers previously documented in the literature [9,15]. In contrast, Company Y's structured adoption of PESI-LCA led to measurable improvements in environmental performance, cost efficiency, and social accountability, validating the framework's practical utility.

Importantly, our findings challenge the assumption that sustainability and profitability are at odds. PESI-LCA enabled Company Y to achieve long-term economic benefits while simultaneously improving ESG compliance and stakeholder trust. These results suggest that integrated LCA frameworks are not just tools for compliance but strategic enablers of sustainable value creation.

While the potential of PESI-LCA is evident, challenges remain, particularly in operationalizing social indicators. Both case companies struggled to quantify social impacts, underscoring the need for more robust and standardized metrics in this domain. Additionally, the study's two-case design, while insightful, limits generalizability. Future research should apply PESI-LCA across a broader range of industries and regulatory contexts to validate its scalability and flexibility.

The case companies were selected based on access and sustainability maturity, which introduces a potential selection bias. Company Y's strong performance may reflect prior organizational culture rather than PESI-LCA alone. Furthermore, the generalizability of the PESI-LCA framework beyond the European policy environment (e.g., CSRD, EU Green Deal) remains to be empirically verified in other regulatory and cultural contexts (e.g., North America, Asia-Pacific). Future research should thus test PESI-LCA in varied institutional settings.

Overall, this study positions PESI-LCA as a valuable addition to the LCA toolbox, one that aligns with global sustainability policy frameworks such as the EU Green Deal and the SDGs, and one that speaks directly to the operational realities of building manufacturing companies. By bridging methodological gaps and enabling more holistic evaluations of product and process sustainability, PESI-LCA advances both the theory and practice of sustainable manufacturing.

6.1 Limitations and Future Research

Given the limited sample of two companies, our empirical support for PESI-LCA is illustrative rather than universal; however, the major differences observed provide a strong proof-of-concept. Future research should include more companies to statistically validate PESI-LCA's applicability across sectors. Additionally, the lack of standardized social impact indicators remains a challenge.

Future research should: (1) explore the integration of digital tools (e.g., blockchain for supply chain transparency, IoT and AI for automated sustainability tracking) into the PESI-LCA framework to enhance data reliability and real-time monitoring; (2) develop quantitative social impact indicators to improve SLCA adoption [6]; (3) future studies should include more case companies across different industries to validate PESI-LCA's applicability and generalize findings [7]; (4) assess Long-Term Financial Impacts of LCA implementation [11].

Ethics Statement

This research involved human participants through semi-structured interviews. The study protocol, including data collection and handling procedures, was reviewed and approved by the Departments Review Board at Linnaeus University, Sweden. All participants provided informed consent prior to the interviews, and all responses were anonymized to ensure confidentiality and privacy in accordance with institutional and GDPR guidelines.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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