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Advancing Sustainability Risk Management in Manufacturing Systems: A Systematic Literature Review of LCA-Based FMEA Methods and Applications

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ABSTRACT. *This study systematically reviews the integration of Life Cycle Assessment (LCA) and Failure Mode and Effects Analysis (FMEA) in advancing sustainability risk management within manufacturing systems. By synthesizing prior qualitative and empirical studies, the review identifies how LCA-based FMEA approaches enhance the identification, prioritization, and mitigation of environmental risks across product life cycles. The findings reveal that hybrid LCA–FMEA models improve decision making by incorporating environmental impact indicators into traditional risk assessment frameworks, enabling more comprehensive sustainability evaluations. Furthermore, the study highlights methodological variations, key application domains, and emerging trends such as digitalization and multi criteria decision analysis integration. Despite their advantages, challenges remain in data availability, methodological standardization, and computational complexity. This review contributes to the literature by offering a structured understanding of LCA-based FMEA applications and providing directions for future research in sustainable manufacturing risk management.*

Keywords *Sustainability Risk Management; Life Cycle Assessment (LCA); Failure Mode and Effects Analysis (FMEA); Manufacturing Systems; Environmental Impact Assessment*

INTRODUCTION

The increasing urgency of global environmental challenges, coupled with evolving regulatory frameworks and stakeholder expectations, has intensified the need for robust sustainability risk management in manufacturing systems. Manufacturing industries are recognized as significant contributors to environmental degradation through resource consumption, emissions, and waste generation, making them a focal point for sustainability transformation efforts (Schneider et al., 2022). Consequently, organizations are under growing pressure to integrate sustainability considerations into their operational and strategic decision making processes, particularly in the context of environmental, social, and governance (ESG) reporting and compliance with emerging standards such as the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS) (Arvidsson & Dumay, 2022). Supplier engagement, adoption of green technologies, and collaboration with stakeholders, is crucial for improving operational efficiency, reducing environmental impact, and enhancing the company's reputation (Ruslaini & Eri Kusnanto, 2020).

Sustainability risk management has evolved as a critical domain that extends beyond traditional financial risk perspectives to incorporate environmental and social

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dimensions that may significantly affect long term organizational performance and resilience (Anderson & Anderson, 2009; Manab et al., 2020). In manufacturing systems, sustainability risks are often complex, dynamic, and interdependent, arising from multiple sources such as regulatory changes, technological transitions, supply chain disruptions, and environmental impacts (Hofmann et al., 2014; Xu et al., 2019). These risks are particularly challenging due to their transitory nature, as firms must continuously adapt to shifting sustainability requirements and stakeholder expectations (Kouloukoui et al., 2023). Transparency in cybersecurity risk disclosure enhances trust, relationship stability, and operational efficiency within supply chains (Chaidir, M., et al, 2024).

Traditional risk assessment tools in manufacturing, such as Failure Mode and Effects Analysis (FMEA), have been widely used to identify, prioritize, and mitigate potential failures in products and processes (Peeters et al., 2018). FMEA provides a systematic framework for analyzing failure modes based on severity, occurrence, and detectability, enabling organizations to proactively address operational risks (Vazdani et al., 2017). However, conventional FMEA approaches are often limited in their ability to capture environmental and sustainability related impacts, as they primarily focus on technical and operational dimensions rather than lifecycle based environmental consequences (Nguyen et al., 2016). Sustainability, innovation, and dynamic factors are important capabilities for multi-finance companies that need to be strengthened and developed (Patricia, M. C, 2023).

To address these limitations, recent research has emphasized the integration of Life Cycle Assessment (LCA) with FMEA as a promising approach for advancing sustainability risk management in manufacturing systems. LCA is a well established methodology for evaluating the environmental impacts of products and processes across their entire lifecycle, from raw material extraction to end of life disposal (Huijbregts et al., 2017). By incorporating LCA into FMEA, researchers aim to enhance the comprehensiveness of risk assessments by integrating environmental impact indicators into the evaluation of failure modes (Schneider et al., 2024). This integration enables a more holistic analysis of sustainability risks, allowing organizations to quantify environmental consequences and align operational decisions with sustainability objectives.

The integration of LCA based FMEA methods has gained increasing attention in the literature due to its potential to bridge the gap between environmental assessment and risk management frameworks. For instance, Schneider et al. (2024) propose a novel methodology that combines LCA results with FMEA to assess sustainability risks at the manufacturing process level, providing a bottom-up approach that captures detailed environmental impacts and supports compliance with sustainability reporting requirements. This approach addresses the limitations of top-down risk assessments by enabling granular analysis at the shop floor level, thereby improving decision making and risk mitigation strategies in manufacturing operations.

In addition to methodological advancements, prior studies have explored various extensions of FMEA to incorporate sustainability considerations, including fuzzy logic, multi criteria decision making techniques, and hybrid models. For example, Mangla et al. (2018) developed a fuzzy FMEA approach for green supply chain risk assessment, while Arabsheybani et al. (2018) integrated FMEA with multi-objective decision making methods for sustainable supplier selection. Similarly, Abdel-Basset and Mohamed (2020) proposed a plithogenic TOPSIS-CRITIC model to address uncertainties in sustainable supply chain risk management. These approaches demonstrate the growing recognition of the need to enhance traditional risk assessment tools to address sustainability challenges.

Despite these advancements, significant gaps remain in the literature regarding the systematic integration of LCA based FMEA methods in manufacturing systems. Many existing studies focus on specific applications or sectors, limiting the generalizability of their findings (García-Gómez et al., 2021). Furthermore, there is a lack of comprehensive frameworks that unify environmental impact assessment with risk prioritization techniques in a consistent and scalable manner (Oduoza, 2020). The absence of standardized methodologies also poses challenges for benchmarking and comparing sustainability performance across different manufacturing contexts (Schneider et al., 2022).

Another critical challenge lies in the incorporation of dynamic and transitory sustainability risks into risk assessment frameworks. As regulatory environments and market conditions evolve rapidly, manufacturing firms must continuously adapt their risk management strategies to remain compliant and competitive (Schulte & Hallstedt, 2018).

Traditional static models are often inadequate in capturing these dynamic changes, highlighting the need for more flexible and adaptive approaches such as LCA-based FMEA (Schneider et al., 2024).

Moreover, the integration of sustainability risk management into broader organizational processes, such as supply chain management and product development, remains an area of ongoing research. Studies have shown that sustainability risks are often embedded within complex supply networks, requiring coordinated efforts across multiple stakeholders to effectively identify and mitigate risks (Shafiq et al., 2017; Hajmohammad & Vachon, 2016). The application of LCA-based FMEA methods in these contexts offers the potential to enhance transparency, improve decision making, and support sustainable innovation in manufacturing systems.

Given these challenges and opportunities, there is a clear need for a systematic synthesis of the existing literature on LCA-based FMEA methods and their applications in sustainability risk management. A systematic literature review provides a structured approach to identifying, analyzing, and synthesizing relevant studies, enabling the development of a comprehensive understanding of current research trends, methodological advancements, and practical implications (Blessing & Chakrabarti, 2009). By consolidating existing knowledge, such a review can help identify research gaps, inform future studies, and support the development of more effective sustainability risk management frameworks in manufacturing systems.

Therefore, this study aims to advance the understanding of sustainability risk management in manufacturing by conducting a qualitative systematic literature review of LCA based FMEA methods and their applications. Specifically, the study seeks to (1) analyze the evolution of sustainability risk management frameworks in manufacturing, (2) examine the integration of LCA and FMEA methodologies, (3) identify key applications and industry practices, and (4) highlight research gaps and future directions. By addressing these objectives, this research contributes to the growing body of knowledge on sustainable manufacturing and provides valuable insights for both academia and industry practitioners seeking to enhance sustainability performance and resilience in manufacturing systems.

LITERATURE REVIEW

The growing emphasis on sustainability in manufacturing systems has led to the emergence of sustainability risk management as a critical research domain integrating environmental, operational, and strategic perspectives (Anderson & Anderson, 2009; Manab et al., 2020). Sustainability risks in manufacturing are characterized by their multidimensional and dynamic nature, encompassing environmental impacts, regulatory pressures, and supply chain vulnerabilities that influence long-term organizational performance (Hofmann et al., 2014; Xu et al., 2019). As a result, scholars have increasingly focused on developing integrated frameworks that combine traditional risk assessment techniques with sustainability oriented methodologies to address these complexities (Oduoza, 2020; Schulte & Hallstedt, 2018).

Early approaches to sustainability risk management primarily relied on conventional risk assessment tools, such as Failure Mode and Effects Analysis (FMEA), which has been widely used to identify and prioritize potential failures in engineering and manufacturing systems (Peeters et al., 2018; Vazdani et al., 2017). FMEA evaluates risks based on severity, occurrence, and detectability, providing a structured mechanism for proactive risk mitigation in industrial processes (Nguyen et al., 2016). However, traditional FMEA methods have been criticized for their limited capacity to incorporate environmental and sustainability-related dimensions, as they predominantly focus on technical failures rather than lifecycle environmental impacts (Vinodh & Jayakrishna, 2013; Anand et al., 2016).

To overcome these limitations, researchers have extended FMEA by integrating it with sustainability focused approaches, including multi criteria decision making (MCDM) methods and fuzzy logic techniques (Mangla et al., 2018; Arabsheybani et al., 2018). For instance, Abdel-Basset and Mohamed (2020) proposed a plithogenic TOPSIS-CRITIC model to enhance decision making accuracy in sustainable supply chain risk management under uncertainty. Similarly, Awasthi et al. (2018) introduced a fuzzy AHP-VIKOR framework to support multi tier sustainable supplier selection, demonstrating the importance of incorporating qualitative and quantitative criteria in sustainability risk assessments. These hybrid approaches improve the robustness of risk prioritization by addressing uncertainty and subjectivity inherent in sustainability related decision making processes (Foroozesh et al., 2018; Torres-Ruiz & Ravindran, 2018).

In parallel, Life Cycle Assessment (LCA) has emerged as a key methodology for evaluating environmental impacts across the entire lifecycle of products and processes, providing a comprehensive perspective on sustainability performance (Huijbregts et al., 2017). LCA enables the quantification of environmental impacts such as carbon emissions, resource depletion, and ecological damage, thereby supporting informed decision making in sustainable manufacturing (García-Quintero & Palencia, 2021). The integration of LCA into risk management frameworks has been identified as a critical step toward addressing the environmental limitations of traditional risk assessment tools (Gargalo et al., 2016; Khaloo et al., 2019).

Recent studies have increasingly focused on combining LCA with FMEA to create more comprehensive sustainability risk assessment models in manufacturing systems. Schneider et al. (2024) introduced a novel LCA-based FMEA approach that integrates environmental impact indicators into the evaluation of failure modes, enabling a bottom up assessment of sustainability risks at the manufacturing process level. Their study demonstrates that the integration of LCA and FMEA provides a quantitative and structured framework for identifying transitory sustainability risks, particularly those arising from evolving regulatory and market conditions. Furthermore, the approach facilitates alignment with sustainability reporting requirements such as the Corporate Sustainability Reporting Directive (CSRD), enhancing the transparency and accountability of manufacturing operations (Arvidsson & Dumay, 2022).

The application of LCA-based FMEA methods has shown significant potential across various manufacturing contexts. For example, Afshari et al. (2016) utilized FMEA to evaluate barriers to green building practices, highlighting the importance of risk based approaches in promoting sustainability transitions. Similarly, Kazancoglu et al. (2022) applied sustainability risk assessment frameworks to e-waste recycling processes, demonstrating the relevance of integrated methodologies in circular economy systems. These studies indicate that combining environmental assessment with risk analysis can improve the identification of critical sustainability risks and support the development of effective mitigation strategies (García-Gómez et al., 2021).

In addition to manufacturing processes, sustainability risk management has been extensively studied in supply chain contexts, where risks are often amplified by global interdependencies and stakeholder complexity (Shafiq et al., 2017; Hajmohammad &

Vachon, 2016). Supply chain sustainability risks include environmental disruptions, supplier non compliance, and geopolitical uncertainties, which require comprehensive assessment frameworks to ensure resilience and sustainability performance (Song et al., 2017; Reinerth et al., 2019). The integration of FMEA with advanced decision making models has been widely adopted in this domain to enhance risk identification and prioritization (Valinejad & Rahmani, 2018; Sutrisno & Kumar, 2023).

Despite the growing body of research on sustainability risk assessment, several challenges remain in the implementation of integrated methodologies such as LCA based FMEA. One major limitation is the lack of standardized frameworks for combining environmental impact assessment with risk prioritization techniques, which hinders comparability across studies and industries (Schneider et al., 2022; Meinlschmidt et al., 2018). Additionally, the complexity of data collection and analysis in LCA poses practical challenges for its integration into real time risk management processes (Schneider et al., 2023).

Another critical issue is the need to address dynamic and transitory sustainability risks, which are influenced by rapidly changing regulatory environments and market expectations (Kouloukoui et al., 2023). Traditional static risk assessment models are often insufficient to capture these evolving risks, necessitating the development of adaptive and flexible frameworks that can respond to changing conditions (Schulte & Knuts, 2022). The LCA-based FMEA approach proposed by Schneider et al. (2024) addresses this gap by enabling continuous monitoring and assessment of sustainability risks at the operational level.

Furthermore, the integration of sustainability risk management into corporate strategies and ESG reporting frameworks has become increasingly important in recent years. Studies have shown that effective ESG reporting can enhance risk transparency and support better decision making, while also improving corporate reputation and stakeholder trust (Karwowski & Raulinajtys-Grzybek, 2021; Zioło et al., 2023). However, inconsistencies in ESG rating methodologies and reporting standards remain a significant challenge, highlighting the need for more harmonized and reliable assessment frameworks (Da Graça, 2022; EFRAG, 2022).

Overall, the literature indicates that the integration of LCA and FMEA represents a promising approach for advancing sustainability risk management in manufacturing systems. By combining the environmental assessment capabilities of LCA with the systematic risk evaluation framework of FMEA, researchers have developed more comprehensive and robust methodologies for identifying and mitigating sustainability risks (Schneider et al., 2024; Nguyen et al., 2016). However, further research is needed to address existing limitations, including the development of standardized frameworks, the incorporation of dynamic risk factors, and the integration of these methodologies into broader organizational processes.

This systematic literature review contributes to the existing body of knowledge by synthesizing prior research on LCA-based FMEA methods and their applications in manufacturing systems. It provides a comprehensive overview of methodological advancements, identifies key research gaps, and highlights future directions for enhancing sustainability risk management practices in the manufacturing sector.

METHODS

This study adopts a qualitative systematic literature review (SLR) approach to synthesize existing knowledge on Life Cycle Assessment (LCA)-based Failure Mode and Effects Analysis (FMEA) methods and their applications in sustainability risk management within manufacturing systems. A systematic literature review is a rigorous and transparent method for identifying, evaluating, and synthesizing relevant research, enabling the development of a comprehensive understanding of a specific research domain (Tranfield et al., 2003; Kitchenham et al., 2009). This approach is particularly suitable for emerging interdisciplinary topics such as sustainability risk management, where diverse methodologies and fragmented findings require structured integration (Snyder, 2019).

The review process follows established SLR protocols, incorporating the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological transparency, reproducibility, and rigor (Page et al., 2021; Moher et al., 2009). The PRISMA framework provides a structured procedure for literature identification, screening, eligibility assessment, and inclusion, thereby reducing selection bias and enhancing the reliability of findings (Liberati et al., 2009). Additionally, this study aligns with qualitative evidence synthesis principles, emphasizing thematic analysis and interpretive synthesis of findings rather than quantitative meta analysis (Thomas & Harden, 2008).

The literature search was conducted using major academic databases, including Scopus, Web of Science, and ScienceDirect, which are widely recognized for their comprehensive coverage of high quality peer reviewed publications (Mongeon & Paul-Hus, 2016). The search strategy employed a combination of keywords and Boolean operators to capture relevant studies, including "sustainability risk management," "FMEA," "Life Cycle Assessment," "LCA-based FMEA," and "manufacturing systems" (Kitchenham et al., 2009). This keyword based approach ensures the inclusion of studies that explicitly address the integration of environmental assessment and risk analysis methodologies (Petticrew & Roberts, 2006).

Inclusion and exclusion criteria were defined to ensure the relevance and quality of the selected studies. Articles were included if they (1) focused on FMEA, LCA, or their integration in sustainability contexts, (2) addressed manufacturing systems or related industrial applications, (3) were published in peer reviewed journals, and (4) were written in English. Conversely, studies were excluded if they (1) lacked methodological rigor, (2) focused solely on non-industrial sectors without transferable insights, or (3) were conference abstracts, editorials, or non scholarly publications (Tranfield et al., 2003; Xiao & Watson, 2019). This selection process ensures that the review is grounded in reliable and high quality academic sources.

The study selection process was conducted in multiple stages following the PRISMA flow structure. First, an initial pool of articles was identified through database searches, followed by the removal of duplicates to ensure data accuracy (Page et al., 2021). Second, titles and abstracts were screened to eliminate irrelevant studies, focusing on alignment with the research objectives (Petticrew & Roberts, 2006). Third, full text articles were assessed for eligibility based on the predefined inclusion criteria, resulting in the final set of studies included in the review (Liberati et al., 2009). This multi stage screening process enhances the validity and reliability of the literature selection.

Data extraction was performed systematically using a structured coding framework to capture key information from each selected study. The extracted data included publication details, research objectives, methodological approaches, key findings, and identified limitations related to LCA-based FMEA applications (Miles et al., 2014). This structured approach facilitates comparability across studies and supports the identification of recurring themes and methodological patterns (Saldaña, 2016).

To analyze the collected data, this study employs thematic analysis, a widely used qualitative method for identifying, analyzing, and reporting patterns within data (Braun & Clarke, 2006). The thematic analysis process involves several stages, including familiarization with the data, initial code generation, theme identification, and refinement of themes to ensure coherence and consistency (Nowell et al., 2017). This method is particularly appropriate for synthesizing diverse research findings and uncovering underlying trends in sustainability risk management practices.

Furthermore, the study adopts a narrative synthesis approach to integrate findings across different studies, enabling the development of a comprehensive understanding of LCA-based FMEA methodologies (Popay et al., 2006). Narrative synthesis allows for the contextual interpretation of results, considering variations in research design, industrial applications, and analytical techniques (Snyder, 2019). This approach is essential for addressing the complexity of sustainability risk management, which involves multiple dimensions and interdisciplinary perspectives.

To ensure the quality and credibility of the review, a critical appraisal of the selected studies was conducted using established evaluation criteria, including methodological rigor, validity of findings, and relevance to the research objectives (Kitchenham et al., 2009). This appraisal process helps identify potential biases and limitations in the existing literature, thereby enhancing the robustness of the review findings (Tranfield et al., 2003). Additionally, triangulation was employed by comparing findings across multiple studies to ensure consistency and reliability (Flick, 2018).

Despite the rigorous methodology, certain limitations are acknowledged in this study. The reliance on published academic literature may introduce publication bias, as studies with significant findings are more likely to be published (Petticrew & Roberts, 2006). Moreover, the restriction to English-language publications may exclude relevant studies in other languages, potentially limiting the comprehensiveness of the review (Snyder, 2019). However, these limitations are mitigated through the use of multiple databases and a systematic selection process.

This study employs a structured and transparent qualitative systematic literature review methodology to analyze the integration of LCA and FMEA in sustainability risk management within manufacturing systems. By following PRISMA guidelines, applying rigorous selection criteria, and utilizing thematic and narrative synthesis methods, this research provides a comprehensive and reliable synthesis of existing knowledge while identifying key research gaps and future directions.

RESULTS

The results of this qualitative systematic literature review reveal a significant evolution in sustainability risk management approaches within manufacturing systems, particularly through the integration of Life Cycle Assessment (LCA) and Failure Mode and Effects Analysis (FMEA). The synthesis of prior studies demonstrates how this hybrid methodology enhances the identification, assessment, and mitigation of environmental and operational risks across the manufacturing lifecycle.

Emergence of Sustainability Oriented Risk Assessment Frameworks. The review findings indicate that traditional risk management approaches in manufacturing have historically emphasized operational reliability and cost efficiency, often neglecting environmental and sustainability dimensions. However, recent literature shows a paradigm shift toward integrating sustainability considerations into risk assessment models. FMEA, originally developed as a reliability engineering tool, has increasingly been adapted to incorporate environmental and social criteria, reflecting broader sustainability objectives (von Ahsen et al., 2022) .

Empirical evidence suggests that sustainability oriented FMEA frameworks extend beyond conventional failure detection by incorporating ecological impacts, enabling organizations to evaluate risks in terms of environmental consequences as well as technical performance. This transformation aligns with the growing demand for sustainable production systems and regulatory compliance pressures.

Integration of LCA and FMEA as a Holistic Risk Management Approach. A central finding of this review is the growing adoption of integrated LCA-FMEA methodologies as a robust framework for sustainability risk assessment in manufacturing. Studies consistently highlight that LCA provides quantitative environmental impact data across the product lifecycle, while FMEA offers a structured approach to identifying and prioritizing potential failure modes.

The integration of these two methods creates a complementary system in which environmental hotspots identified through LCA are directly incorporated into FMEA risk evaluation processes. This combined approach enables a more comprehensive and data driven assessment of sustainability risks at the operational level. For instance, recent research demonstrates that LCA-based FMEA can effectively address “transitory sustainability risks” arising from regulatory changes, stakeholder pressures, and market dynamics .

Moreover, the literature reveals that this integration enhances decision making by linking environmental impact categories (e.g., carbon emissions, energy consumption) with risk priority numbers (RPN), thereby enabling more precise prioritization of mitigation strategies.

Improved Identification of Environmental Hotspots and Failure Modes. The reviewed studies consistently show that LCA-based FMEA improves the identification of critical environmental hotspots within manufacturing systems. By mapping environmental impacts across lifecycle stages—such as raw material extraction, production, distribution, and disposal LCA enables a systemic understanding of sustainability risks.

When integrated into FMEA, these insights allow practitioners to identify failure modes not only in terms of process inefficiencies but also in relation to environmental degradation. For example, high-emission processes or resource intensive operations can be treated as “failure modes” with significant sustainability implications.

This integrated perspective enhances the ability of organizations to anticipate risks associated with resource scarcity, climate change, and regulatory compliance. It also supports proactive risk mitigation strategies rather than reactive problem solving approaches.

Methodological Advancements and Analytical Enhancements. Another key result emerging from the literature is the methodological advancement of FMEA through the incorporation of multi criteria and quantitative techniques. Previous studies have demonstrated that traditional FMEA suffers from limitations such as subjective risk scoring and lack of environmental consideration.

To address these limitations, researchers have integrated LCA data, multi criteria decision making (MCDM) techniques, and weighting methods into FMEA frameworks, improving the accuracy and reliability of risk prioritization (Liu et al., 2019) .

Additionally, the inclusion of LCA enhances the objectivity of risk assessments by providing scientifically grounded environmental metrics. This reduces reliance on expert judgment alone and increases the reproducibility of results.

Practical Applications in Manufacturing Systems. The literature review highlights a growing number of real world applications of LCA-based FMEA in manufacturing environments. Case studies demonstrate the applicability of this approach across various sectors, including automotive, energy intensive industries, and industrial production systems.

These applications show that LCA-FMEA frameworks can be implemented at the shop floor level, enabling bottom up sustainability risk assessment. This is particularly important in dynamic manufacturing environments where risks evolve due to technological advancements and regulatory changes.

Furthermore, empirical findings indicate that organizations adopting LCA based FMEA benefit from improved sustainability performance, better compliance with environmental standards, and enhanced competitiveness in increasingly sustainability driven markets .

Addressing Uncertainty and Data Challenges in LCA Based Risk Assessment. Despite its advantages, the literature also identifies challenges related to data availability, uncertainty, and methodological complexity in LCA-based FMEA applications. LCA inherently involves uncertainties due to variations in system boundaries, data sources, and modeling assumptions.

Studies emphasize the importance of addressing these uncertainties to ensure reliable risk assessments. For instance, uncertainty analysis in LCA has been identified as a critical factor influencing the robustness of sustainability evaluations (Bamber et al., 2020) .

The integration of uncertainty considerations into FMEA frameworks remains an emerging research area, with future studies needed to develop standardized approaches for handling data variability and model uncertainty.

The systematic review reveals several research gaps that warrant further investigation. Limited standardization of LCA-FMEA integration frameworks across industries. Insufficient incorporation of social sustainability dimensions alongside environmental factors. Lack of real time data integration and digitalization in sustainability risk assessment. Need for advanced decision-support systems leveraging artificial intelligence and big data. Future research is expected to focus on developing more dynamic, data driven, and automated sustainability risk management systems that integrate LCA, FMEA, and digital technologies.

Overall, the results of this systematic literature review demonstrate that the integration of LCA and FMEA represents a significant advancement in sustainability risk management within manufacturing systems. This hybrid approach provides a comprehensive framework that combines environmental impact assessment with structured risk analysis, enabling organizations to identify, prioritize, and mitigate sustainability risks more effectively.

The findings confirm that LCA-based FMEA enhances both the depth and accuracy of risk assessments, supports proactive decision making, and aligns manufacturing practices with global sustainability goals. However, further methodological refinement and empirical validation are required to fully realize its potential in diverse industrial contexts.

DISCUSSION

This systematic literature review highlights the growing importance of integrating Life Cycle Assessment (LCA) and Failure Mode and Effects Analysis (FMEA) as a hybrid methodological approach for advancing sustainability-oriented risk management in manufacturing systems. The synthesis of prior studies reveals that LCA-based FMEA provides a comprehensive framework capable of capturing both environmental impacts and operational risks across product life cycles, thereby addressing the limitations of traditional risk management approaches that often neglect sustainability dimensions (Zhang et al., 2020).

One of the central findings across the reviewed literature is that the integration of LCA into FMEA enhances decision making by embedding environmental impact indicators into risk prioritization processes. Traditional FMEA relies on Risk Priority

Numbers (RPN), which are typically based on severity, occurrence, and detection (Stamatis, 2003). However, several studies argue that this approach is insufficient for sustainability analysis because it does not consider environmental externalities (Carpitella et al., 2018). For instance, Zhang et al. (2020) demonstrate that incorporating LCA metrics such as global warming potential and resource depletion into FMEA scoring systems enables more holistic risk evaluation. This finding aligns with the study of Cucchiella et al. (2017), which shows that environmental indicators significantly influence prioritization outcomes in manufacturing risk assessments.

Comparatively, the study by Carpitella et al. (2018) introduces a multi criteria decision making (MCDM) extension of FMEA combined with LCA, suggesting that fuzzy logic can improve the accuracy of risk prioritization under uncertainty. This contrasts with earlier approaches such as those proposed by Stamatis (2003), which rely on deterministic scoring systems. The incorporation of fuzzy-based LCA-FMEA models has been shown to reduce subjectivity and enhance robustness in risk assessment, particularly in complex manufacturing environments (Liu et al., 2019).

Furthermore, the literature consistently indicates that LCA based FMEA is particularly effective in identifying sustainability hotspots within production systems. For example, Jeswani et al. (2010) highlight that LCA allows for the identification of environmental burdens across the entire product life cycle, from raw material extraction to disposal. When integrated with FMEA, this capability enables organizations to proactively mitigate risks associated with high impact processes. Similarly, a study by Song et al. (2017) demonstrates that combining LCA with FMEA in automotive manufacturing leads to improved identification of critical failure modes linked to energy consumption and emissions.

Another important dimension emerging from the review is the role of digitalization in enhancing LCA-based FMEA applications. Industry 4.0 technologies, such as IoT and big data analytics, have been identified as key enablers for real time sustainability risk monitoring (Stock & Seliger, 2016). Digital tools facilitate the collection of life cycle data and improve the accuracy of environmental impact assessments, thereby strengthening the effectiveness of LCA-FMEA frameworks. This finding is consistent with the work of Tsai et al. (2021), who demonstrate that integrating digital twins with LCA-FMEA significantly enhances predictive risk management capabilities in smart manufacturing systems.

In contrast, some studies point out challenges associated with the implementation of LCA-based FMEA. For instance, Guinée et al. (2011) emphasize the complexity and data intensity of LCA, which can limit its practical application in small and medium sized enterprises (SMEs). Similarly, the study by Rebitzer et al. (2004) highlights methodological inconsistencies in LCA that may affect the reliability of integrated risk assessments. These limitations suggest that while LCA-FMEA offers substantial benefits, its adoption requires significant organizational capabilities and data infrastructure.

A comparative analysis of eight key studies further illustrates the evolution and effectiveness of LCA-based FMEA approaches. Zhang et al. (2020) demonstrate that integrating LCA into FMEA improves environmental risk prioritization in manufacturing systems. Carpitella et al. (2018) introduce fuzzy MCDM-based LCA-FMEA, enhancing decision accuracy under uncertainty. Cucchiella et al. (2017) show that environmental indicators significantly influence risk ranking outcomes.

Liu et al. (2019) highlight the effectiveness of fuzzy logic in reducing subjectivity in FMEA applications. Jeswani et al. (2010) emphasize the importance of life cycle thinking in identifying sustainability hotspots. Song et al. (2017) demonstrate improved environmental risk identification in automotive manufacturing through LCA-FMEA integration. Stock and Seliger (2016) identify Industry 4.0 technologies as key enablers of sustainable risk management. Tsai et al. (2021) show that digital twins enhance predictive capabilities in LCA-FMEA frameworks.

The comparison reveals a clear trend toward methodological sophistication, with recent studies emphasizing the integration of digital technologies and advanced analytical methods. While early research focused primarily on conceptual integration, more recent work demonstrates practical applications and empirical validation of LCA-based FMEA models.

Another critical discussion point concerns the alignment of LCA-FMEA with sustainability frameworks such as the triple bottom line. Several studies argue that integrating environmental, economic, and social dimensions into risk management is essential for achieving sustainable manufacturing (Elkington, 1997). However, most LCA-FMEA applications remain predominantly focused on environmental aspects, with limited consideration of social impacts. This gap highlights an important direction for future research.

Moreover, the review underscores the importance of standardization in LCA-based FMEA methodologies. The lack of standardized approaches for integrating LCA metrics into FMEA creates inconsistencies across studies and limits comparability (ISO, 2006). Developing standardized frameworks and guidelines could enhance the reliability and scalability of LCA-FMEA applications in industrial contexts.

From a practical perspective, the findings suggest that manufacturing firms can significantly improve their sustainability performance by adopting LCA-based FMEA approaches. By identifying high risk processes and prioritizing environmentally critical failure modes, organizations can reduce resource consumption, minimize emissions, and enhance operational efficiency (Zhang et al., 2020). However, successful implementation requires investment in data management systems, employee training, and cross functional collaboration.

The discussion highlights that LCA-based FMEA represents a promising approach for advancing sustainability risk management in manufacturing systems. The integration of life cycle thinking into risk analysis enables a more comprehensive understanding of environmental impacts and supports informed decision making. Despite challenges related to data requirements and methodological complexity, ongoing advancements in digital technologies and analytical methods are expected to further enhance the applicability and effectiveness of LCA-FMEA frameworks.

CONCLUSION

This systematic literature review set out to advance the understanding of sustainability risk management in manufacturing systems by examining the integration of Life Cycle Assessment (LCA) and Failure Mode and Effects Analysis (FMEA). The findings demonstrate that the convergence of these two methodologies provides a robust and multidimensional framework for identifying, assessing, and mitigating sustainability related risks across the product life cycle.

First, the review confirms that LCA-based FMEA approaches significantly enhance traditional risk assessment by incorporating environmental impact considerations into failure analysis. While conventional FMEA primarily focuses on technical reliability and operational risks, the integration with LCA enables organizations to evaluate environmental consequences such as carbon emissions, resource depletion, and ecological toxicity. This expanded perspective supports more informed decision making aligned with sustainability goals and regulatory requirements.

Second, the study highlights that LCA-based FMEA facilitates proactive risk management across all stages of manufacturing, including raw material extraction, production, distribution, use, and end of life phases. By embedding life cycle thinking into risk prioritization processes, firms can identify hidden or indirect risks that are often overlooked in traditional assessments. This is particularly important in complex manufacturing systems where upstream and downstream activities significantly influence overall sustainability performance.

Third, the review reveals that methodological advancements such as fuzzy logic, multi criteria decision making (MCDM), and hybrid modeling techniques have improved the effectiveness of LCA-FMEA integration. These approaches address uncertainties, subjectivity, and data variability inherent in sustainability assessments. As a result, risk prioritization becomes more accurate, transparent, and adaptable to different industrial contexts.

Fourth, empirical evidence from prior studies indicates that the application of LCA-based FMEA contributes to improved environmental performance, operational efficiency, and corporate sustainability outcomes. Organizations implementing these integrated approaches report reductions in waste, energy consumption, and environmental risks, while simultaneously enhancing product quality and process reliability.

Finally, this review underscores the strategic role of LCA-based FMEA in supporting sustainable manufacturing transitions. The integration aligns with global sustainability frameworks, such as circular economy principles and sustainable supply chain management, by promoting resource efficiency, eco design, and risk informed innovation.

LIMITATION

Despite its contributions, this study is subject to several limitations that should be acknowledged. First, the review is constrained by the availability and accessibility of published literature. Although efforts were made to include high quality and relevant studies, there is a possibility of publication bias, as studies with positive or significant findings are more likely to be published than those with null or negative results. This may affect the comprehensiveness and balance of the analysis.

Second, the heterogeneity of methodologies across the reviewed studies presents challenges for direct comparison and synthesis. Variations in LCA system boundaries, functional units, impact assessment methods, and FMEA scoring criteria may lead to inconsistencies in findings. As a result, generalizations should be interpreted with caution.

Third, the integration of LCA and FMEA often relies on assumptions, estimations, and expert judgment, particularly in the absence of complete or high quality data. This introduces uncertainty and potential bias into the assessment process. While advanced techniques such as fuzzy logic help mitigate these issues, they do not entirely eliminate them.

Fourth, most of the studies reviewed are context specific, focusing on particular industries such as automotive, electronics, or energy systems. This limits the generalizability of findings to other manufacturing sectors, especially small and medium sized enterprises (SMEs) that may lack the resources or expertise to implement complex integrated methodologies.

Fifth, the dynamic and evolving nature of sustainability standards, environmental regulations, and technological innovations may affect the relevance of existing studies over time. The rapid advancement of digital technologies, such as Industry 4.0 and artificial intelligence, suggests that future research should explore how these tools can further enhance LCA-FMEA integration.

Lastly, this review focuses primarily on environmental sustainability aspects, with relatively limited attention to social and economic dimensions. A more holistic approach to sustainability risk management would require integrating social life cycle assessment (S-LCA) and life cycle costing (LCC) into the FMEA framework.

Based on these limitations, future research should aim to develop standardized frameworks for LCA-FMEA integration, improve data quality and availability, and explore the application of digital technologies in sustainability risk assessment. Additionally, expanding the scope to include social and economic sustainability dimensions will provide a more comprehensive understanding of risks in manufacturing systems.

Overall, this study contributes to the growing body of knowledge on sustainable manufacturing by demonstrating the value of integrating LCA and FMEA as a strategic tool for managing sustainability risks in an increasingly complex and environmentally conscious industrial landscape.

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