International Journal of
Industrial and Product Design Engineering

Volume 2, Issue 2, 2024
July—December
DOI (Journal): 10.37591/IJIPDE

https://journals.stmjournals.com/ijipde

Review IJIPDE

Realtime Life Cycle Assessment, Synthesizing Life Cycle Inventory with Business Process Management, Sustainable Growth in the Fourth Industrial Revolution

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Abstract

A prevalent methodology for evaluating the ecological impacts of processes and products throughout their entire life cycle is known as Life Cycle Assessment (LCA). This approach involves scrutinizing each phase, encompassing the extraction of raw materials, manufacturing, utilization, and disposal. Nevertheless, conventional LCA methods often fail to account for the dynamic nature of industrial processes and are deficient in real-time data. The Life Cycle Inventory (LCI), a pivotal component of LCA, demands significant time and energy resources and is predominantly reliant on a substantial corpus of data. Leveraging this extensive dataset not only holds potential for streamlining the LCA process but also for enhancing environmental sustainability initiatives. The aim of this discourse is to introduce and elucidate the application of a Dynamic Life Cycle Assessment (LCA) system, which integrates Business Intelligence (BI) software with an Enterprise Resource Planning (ERP) system. This exposition draws upon a case study involving an Italian ceramic tile factory. The model underwent rigorous validation testing iterations to ensure the integrity of the IT architecture and to analyze both the static and dynamic environmental impacts. The efficacy of the validation procedures was evidenced, establishing the Dynamic LCA system as a valuable tool for evaluating and monitoring the environmental ramifications entwined with production processes.

Keywords: Life cycle inventory LCI, Enterprise resource planning ERP, Life Cycle Assessment LCA

INTRODUCTION

In the era of Industry 4.0, which emphasizes the fusion of digital technologies and automation in manufacturing, integrating LCA with Life Cycle Inventory (LCI) and Enterprise Resource Planning (ERP) systems emerges as a method for enhancement. This synergy facilitates a more precise and contemporaneous assessment of environmental implications, furnishing real-time insights into resource utilization, waste generation, and energy consumption. This study presents an abstract framework for dynamic life cycle assessment, amalgamating LCI and ERP systems within an Industry 4.0 paradigm. Leveraging digital technologies such as cloud computing, data analytics, and Internet of Things (IoT) devices, the framework gathers and scrutinizes real-time data across various life cycle phases. Subsequently, this data can be utilized to identify areas necessitating

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Received Date: July 18, 2024
Accepted Date: November 14, 2024
Published Date: November 27, 2024

Citation: Nidhi Sahu, Rohit Singh Lather, Deepal Kumar Bhalla. Realtime Life Cycle Assessment, Synthesizing Life Cycle Inventory with Business Process Management, Sustainable Growth in the Fourth Industrial Revolution. International Journal of Industrial and Product Design Engineering. 2024; 2(2): 1–9p.

improvement and compute environmental metrics. The integration of LCI and ERP systems affords a holistic appraisal of environmental impacts, encompassing not only the direct consequences of products or processes but also the indirect effects stemming from resource utilization and waste generation. By harnessing real-time data, companies can perpetually monitor and refine their environmental performance. By furnishing insights into the environmental repercussions of diverse production scenarios, the proposed framework has the potential to inform industrial decision-making processes. It facilitates the identification of opportunities for waste reduction, resource optimization, and energy conservation, thereby fostering environmentally conscientious and sustainable operations. In conclusion, within an Industry 4.0 context, the integration of LCI and ERP systems stands poised to expedite and refine life cycle assessments, empowering businesses to make informed decisions and bolster their environmental stewardship endeavors. In the contemporary epoch of Industry 4.0, corporations are progressively embracing cutting-edge technologies and digital solutions to streamline operations and enhance sustainability initiatives. One prominent strategy involves amalgamating dynamic life cycle assessment (LCA) with life cycle inventory (LCI) and enterprise resource planning (ERP) systems.

Dynamic LCA epitomizes an evolution of conventional LCA methodologies, aiming to scrutinize the environmental impacts of products or processes across their entire life cycles. This approach acknowledges the fluid nature of systems, considering shifts in technology, energy sources, and material inputs over time. Through the integration of LCI data with ERP systems, corporations can continuously monitor and analyze the environmental performance of their operations in real-time (Figure 1).

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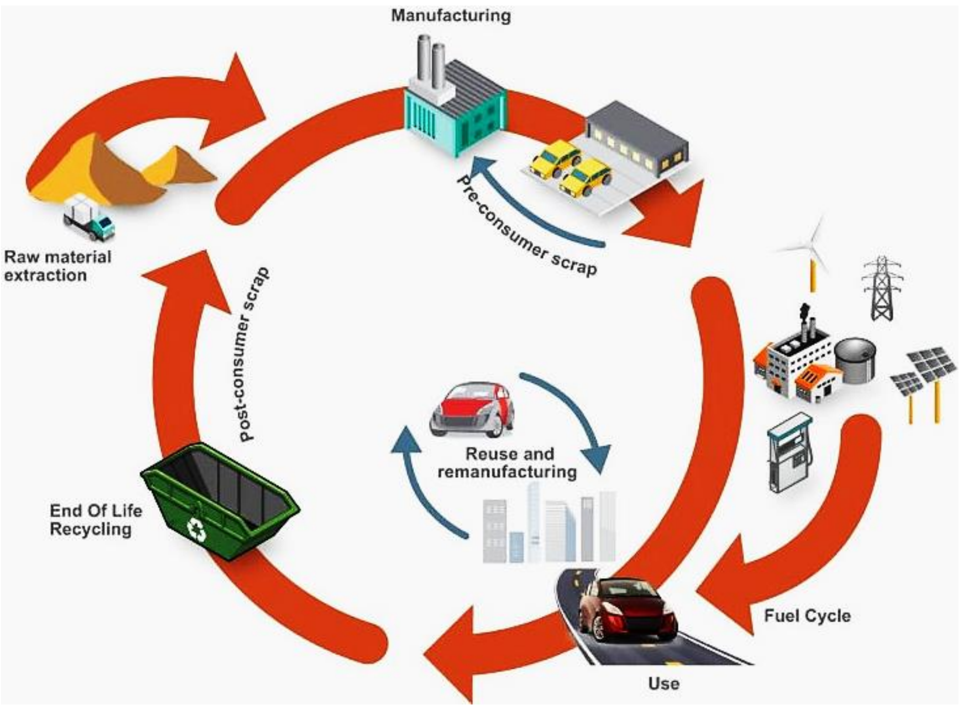

Figure 1. Vehicle LCA encompasses all phases of the product cycle, from raw material extraction to end of life recycling and disposal.

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Despite the emergence of Industry 4.0, the sporadic analysis of LCAs in manufacturing contexts presents a paradox. This era, characterized by the Fourth Industrial Revolution, has ushered in an array of tools, even accessible to small and medium-sized enterprises (SMEs), for monitoring Key Performance Indicators (KPIs) throughout manufacturing phases. Digitization typically transpires through the implementation of Manufacturing Execution Systems (MES), which interface with planning systems (ERP) and control systems (PLC), facilitating the collection and processing of strategic information to enhance production control. Factory 4.0 epitomizes a digitized system capable of aggregating and processing machinery-derived information at every stage of the production process, fostering informed decision-making. With the evolution towards Industry 4.0+, driven by data and artificial intelligence, innovation continues to reshape manufacturing paradigms [1-3].

Enterprise resource planning systems serve as comprehensive software platforms integrating various business functions, such as production planning, inventory management, and supply chain optimization. By amalgamating LCI data with ERP systems, corporations can attain a holistic understanding of their environmental impacts, encompassing resource consumption, waste generation, and emissions (Figure 2).

Figure 2. Enterprise resource planning.

The integration of LCI and ERP systems within Industry 4.0 empowers corporations to make informed decisions concerning process optimization, product design, and supply chain management. Through continuous monitoring and analysis of environmental performance, companies can identify areas ripe for improvement and implement strategies to curtail their carbon footprint and resource utilization.

Moreover, the fusion of LCI and ERP systems equips corporations to respond adeptly to evolving market demands and regulatory frameworks. Armed with real-time data on environmental impacts, companies can adapt operations to align with sustainability objectives and comply with environmental standards [4].

Conceptualizing the flow of data, processes, and interactions between these elements. Here's a basic framework for such a figure:

System Components

Dynamic LCA: This component represents the continuous assessment of environmental impacts throughout the life cycle of a product or process, taking into account changes over time and the dynamic nature of manufacturing processes (Figure 3).

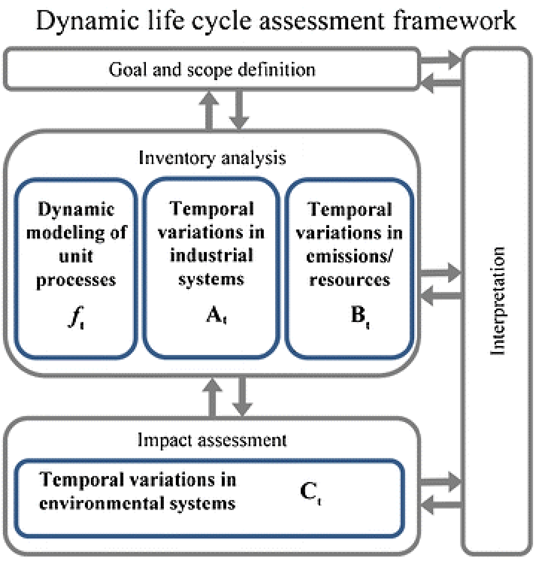

Figure 3. Dynamic life cycle assessment framework.

Life Cycle Inventory (LCI): This component involves the compilation and quantification of inputs and outputs associated with a product or process throughout its life cycle, including resource extraction, production, use, and disposal (Figure 4).

Figure 4. Life cycle inventory.

Life Cycle Inventory
Integrated waste management: A life-cycle inventory

Enterprise Resource Planning (ERP): This component represents the integrated management of core business processes, often including manufacturing, supply chain management, finance, and human resources [5].

Integration Points

Data Exchange: Arrows indicating the flow of data between LCA, LCI, and ERP systems, illustrating how information is shared and utilized between these components.

Real-time Monitoring: Highlighting the ability of ERP systems to provide real-time data on manufacturing processes and resource usage, which can feed into LCA and LCI calculations (Figure 5).

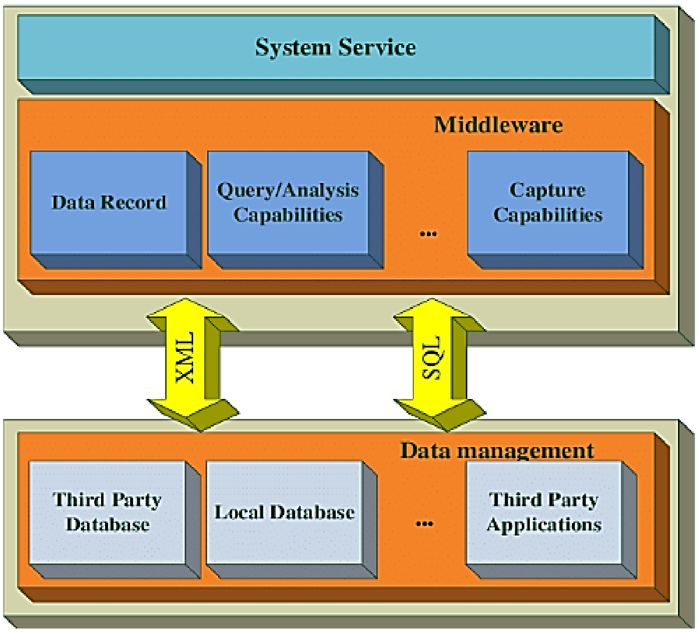

Figure 5. Data Exchange.

Decision Support: Indicating how LCA results can inform decision-making within ERP systems, such as optimizing production processes to reduce environmental impacts or selecting sustainable materials from suppliers [6].

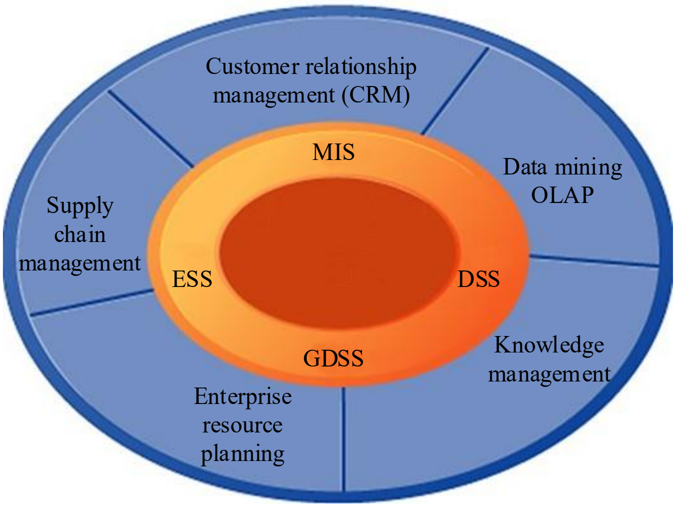

Figure 6. Systems and Technologies for Business Intelligence.

Industry 4.0 Technologies

Internet of Things (IoT): Illustrating how IoT sensors embedded within manufacturing equipment can gather data on energy consumption, emissions, and other relevant parameters, which can then be utilized in LCA and LCI calculations (Figure 6).

Big Data Analytics: Depicting the use of big data analytics tools to process large volumes of data generated by ERP and IoT systems, extracting insights to support sustainability initiatives and decision-making [7,8].

Artificial Intelligence (AI): Showing how AI algorithms can analyze LCA and LCI data, identify patterns, and suggest optimization strategies for minimizing environmental impacts while maximizing efficiency and profitability.

Sustainability Outcomes

Environmental Impact Reduction: Demonstrating the potential for integrating Dynamic LCA and LCI with ERP systems to reduce environmental impacts across the entire life cycle of products and processes.

Resource Efficiency: Highlighting the optimization of resource usage and waste reduction through the application of sustainable manufacturing practices informed by LCA insights.

Long-term Sustainability: Emphasizing the role of integrated LCA-LCI-ERP systems in promoting long-term sustainability and resilience within Industry 4.0 environments [9].

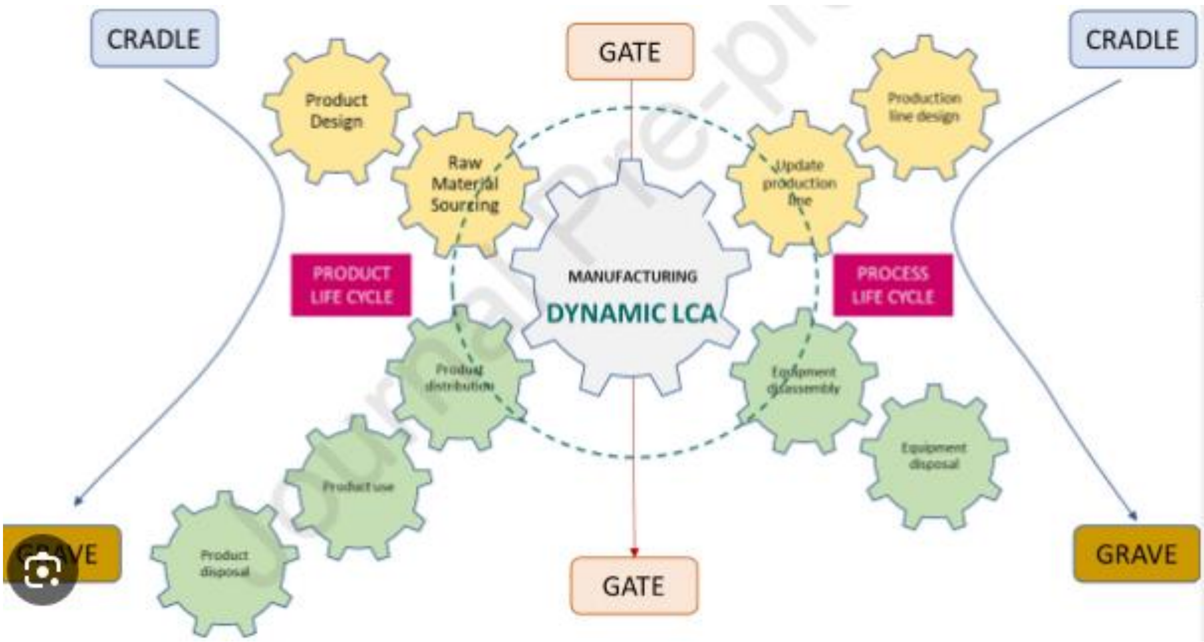

Figure 7. Manufacturing Dynamic LCA.

In summation, the integration of dynamic LCA, LCI, and ERP systems within Industry 4.0 furnishes corporations with a potent tool to bolster sustainability endeavors. By harnessing advanced technologies and data analytics, companies can optimize operations, mitigate environmental impacts, and contribute to a more sustainable future (Figure 7). Nevertheless, it's crucial to note that LCA analyses are typically conducted to fulfill specific objectives, whether academic research pursuits or business-driven environmental certifications, as underscored by Meinrenken, Anthony, and Lackner (2013).

i. The intricacy inherent in inventory analysis and data structuring can act as a deterrent to the widespread adoption of Life Cycle Assessment (LCA), preventing its full utilization of benefits [10].
ii. This complexity also presents challenges in sourcing primary data, leading to the utilization of secondary data from databases as an alternative approach to achieving approximate environmental assessment results in LCA.

iii. Amidst the vast array of inventory inputs, both primary and secondary, only select ones are pivotal in influencing the environmental impact of a given phase within the monitored life cycle.
iv. Attempts to simplify this complexity may overlook crucial facets of LCA, potentially resulting in the dissemination of inaccurate sustainability-related information.
v. With the prevalence of Enterprise Resource Planning Systems (ERPs), many companies already possess a substantial portion of the primary inventory data necessary for conducting LCAs.
vi. Through the utilization of real data streams sourced from ERPs, the complexities, constraints, and inconsistencies inherent in common LCA inventory data can be mitigated. Integration of Business Intelligence with cutting-edge Artificial Intelligence technologies further enhances the processing, analysis, and utilization of real-time data, particularly benefiting manufacturing firms.

Consequently, Several Critical Issues Arise

Inability to utilize Life Cycle Assessment tools for prompt corrective actions on processes and products due to reliance on historical data for impact assessments, thus addressing impacts post-occurrence.

Challenges in the collection and processing of data to conduct impact assessments using conventional techniques.

The necessity for specialized personnel proficient in the usage of commercial software for environmental impact assessment.

Building upon these premises, this paper aims to explore the following research questions (RQs):
RQ1: Can Internet of Things (IoT) technologies and manufacturing models from Industry 4.0 facilitate Life Cycle Inventory (LCI) for LCA studies?

RQ2: Is it feasible to enhance the dynamism of LCA analysis by leveraging the potential of production data collected through ERPs?

RQ3: Can digital manufacturing technologies enable real-time LCA analysis?

METHODOLOGY

Dynamic Life Cycle Assessment (MDLCA) epitomizes a meticulous methodology employed for the comprehensive evaluation of the environmental repercussions associated with a product or process throughout its entire lifespan. This exhaustive scrutiny traverses all stages, ranging from the extraction of raw materials to manufacturing, utilization, and eventual disposal. MDLCA emerges as an invaluable tool for pinpointing areas necessitating enhancements to mitigate environmental impacts and propel sustainability endeavors forward [11].

The Life Cycle Assessment (LCA) undertaken in this inquiry rigorously adheres to the ISO 14040 and ISO 14044 standards, adopting a cradle-to-grave approach. Subsequent sections meticulously expound upon the case study and illuminate the findings derived from it.

Conceptual validation through eco-design assumes a pivotal role in this undertaking.

The integration of Life Cycle Inventory (LCI) data and Enterprise Resource Planning (ERP) systems within the framework of Industry 4.0 entails the assimilation of LCI data into ERP platforms to augment decision-making processes. LCI furnishes intricate insights into the inputs, outputs, and environmental footprints associated with each stage of a product's life cycle. Conversely, ERP systems serve as comprehensive software platforms amalgamating diverse business processes and functions within an organization.

By integrating LCI data into ERP systems, companies can attain a more profound understanding of the environmental impacts stemming from their operations. This integration facilitates informed decision-making concerning resource allocation, production planning, and supply chain management. Furthermore, it empowers companies to monitor and track their environmental performance in real-time, thereby facilitating ongoing improvement initiatives.

Industry 4.0 denotes the fourth industrial revolution characterized by the integration of digital technologies, automation, and data exchange within manufacturing processes. The integration of LCI and ERP systems within the Industry 4.0 paradigm aligns with the overarching objective of leveraging technology to optimize resource efficiency, curtail waste generation, and mitigate environmental impacts.

Within the context of Industry 4.0, the integration of LCI and ERP systems holds immense potential to significantly augment the speed and precision of life cycle assessments, empowering businesses to make well-informed decisions and fortify their environmental performance.

CONCLUSION

Incorporating Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI) into Enterprise Resource Planning (ERP) systems within an Industry 4.0 framework holds significant potential for industries.

By integrating LCA and LCI into ERP systems, businesses can gain comprehensive insights into the environmental impacts of their processes and products throughout their entire life cycles. This integration facilitates the adoption of sustainable practices and enables informed decision-making to minimize environmental footprints.

Real-time data gathering and analysis become feasible through the integration of LCA and LCI with ERP, providing companies with precise and up-to-date information on resource consumption, waste generation, and emissions. This data empowers businesses to identify areas for improvement, enhance operational efficiency, and optimize resource allocation.

Furthermore, integration with ERP allows companies to meet sustainability objectives and regulatory standards by enabling proactive management of environmental impacts and ensuring compliance.

In an Industry 4.0 environment characterized by digitalization, automation, and data exchange, the seamless integration of LCA and LCI with ERP systems becomes increasingly feasible. Through efficient data collection, analysis, and utilization facilitated by this integration, businesses can make data-driven decisions and drive continuous improvement.

Overall, the integration of LCA and LCI with ERP in an Industry 4.0 context offers the potential for environmentally friendly and sustainable operations, enhanced compliance, and more effective decision-making. For companies committed to sustainability and leveraging digital technologies to enhance environmental performance, this strategy proves invaluable.

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