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Dynamic Sustainability Assessment: Enhancing the RAMI 4.0 Model for Environmental Integration in Industry 4.0

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Abstract:
The rapid advancement of digital technologies is reshaping manufacturing, enabling smarter, interconnected systems that redefine industrial processes. While frameworks like the Reference Architectural Model for Industry 4.0 (RAMI 4.0) provide essential guidance for navigating this digital transformation, they overlook a fundamental aspect: the sustainability of processes. Traditionally, environmental impacts are assessed through Life Cycle Assessment (LCA), a well-established methodology. However, LCA's static and retrospective nature struggles to align with the dynamic, real-time capabilities of Industry 4.0. To address this dual challenge, leveraging digitalization while ensuring sustainability, we propose integrating an Environmental Assessment (EA) layer into RAMI 4.0. This additional layer would enable real-time updates of environmental data, supporting continuous optimization of materials and production processes with a strong focus on their ecological implications.

Keywords: Industry 4.0, Reference Architecture Model for Industry 4.0 (RAMI 4.0), Life Cycle Assessment (LCA), Sustainability

1. INTRODUCTION

The advent of Industry 4.0 marks a significant transformation in manufacturing processes *Vaidya et al. (2018)*. This revolution is not only about enhancing efficiency or productivity; but also about redefining the manufacturing landscape through interconnected and intelligent production environments driven by innovative frameworks such as the Reference Architecture Model for Industry 4.0 (RAMI 4.0), that is a comprehensive framework guiding businesses in aligning their Industry 4.0 initiatives. RAMI 4.0 covers various aspects, from the product lifecycle and value stream to hierarchy levels and interoperability standards *DIN (2016)*. However, as the global focus on environmental sustainability intensifies, it becomes clear that technological advances cannot be disconnected from environmental concerns. For this reason, the integration of sustainability practices into the Industry 4.0 paradigm emerges as a critical objective *Oláh et al. (2020)*, requiring a re-evaluation of traditional approaches and a shift towards more ecologically responsible manufacturing methods.

Life Cycle Assessment (LCA) is a well-known methodology for assessing the environmental impact of products throughout their entire lifespan *ISO (2006a)ISO (2006b)*. Nevertheless, LCA suffers from some limitations, notably the difficulty of keeping up-to-date data in the dynamic contexts of production. This issue turns out to be even more relevant for products with extended life cycles *Proske and Finkbeiner (2019)*, whose initial parameters, such as regulatory requirements, geopolitical agreements, supply chain dynamics, or technological advancements, can undergo substantial transformations over time, making initial evaluations obsolete or misleading. Therefore, periodic updates of LCA evaluations are needed to ensure their precision and relevance. To address this gap, the proposal is to integrate the traditional RAMI 4.0 with a new "Environmental Assessment (EA)" layer, which makes environmental analysis a dynamic and updated process.

The following sections of this paper are organized as follows: Section 2 provides an overview of the relevant literature, focusing on the methodologies and applications of Life Cycle Assessment (LCA) and the Reference Architecture Model for Industry 4.0 (RAMI 4.0), along with their intersection in the context of sustainability. Section 3 introduces the proposed solution, detailing the integration of an "Environmental Assessment (EA)" layer within the RAMI 4.0 framework to address the identified gaps. Finally, Section 4 presents the conclusions, highlighting the contributions of this study, its limitations, and potential directions for future research.

2. LCA AND RAMI 4.0

LCA is internationally standardized by the International Organization for Standardization (ISO) under the ISO 14040 series and is a well-established methodology, with its origins tracing back to the 1960s and early 1970s *Guinée*

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et al. (2010), used to assess the environmental aspects and potential impacts associated with a product, process, or service across all stages of its life cycle, from raw material extraction ("cradle") through production, use, and disposal ("grave") *ISO (2006a), ISO (2006b)*. The LCA methodology (see Figure 1) is structured into four main phases: goal definition and scope, inventory analysis, impact assessment, and interpretation.

Fig. 1. *Four steps of LCA methodology*

This systematic approach ensures that all relevant environmental impacts are taken into account. The specific steps involved are:

- Goal and Scope Definition: This initial phase involves stating the purpose of the study, the intended application, the functional unit, which provides a quantifiable measure of the product system's performance, and establishing system boundaries to identify the extent of the life cycle stages considered. Common system boundaries include **Cradle-to-Grave**: Encompasses all stages from raw material extraction (cradle) through production, distribution, use, and final disposal (grave). **Cradle-to-Gate**: Includes processes from raw material extraction up to the factory gate, focusing on the production phase and excluding the use and end-of-life stages. **Gate-to-Gate**: Examines a specific segment of the production process. **Cradle-to-Cradle**: Emphasizes recycling and the creation of a closed-loop system where the product at the end of its life becomes the input for new products *Guinee (2001)*.
- Life Cycle Inventory (LCI) Analysis: In this phase, data are collected and compiled to quantify energy and raw material requirements, emissions to air, water, and soil, and other environmental aspects for all processes within the system boundaries. The LCI provides a detailed and exhaustive account of all inputs and outputs related to the product system. *Guinee (2001)*.
- Life Cycle Impact Assessment (LCIA): The LCIA phase evaluates the potential environmental impacts based on the LCI data. This involves several steps: **Classification**: Assigning LCI results to relevant environmental impact categories (e.g., global warming, acidification, eutrophication). **Characterization**: Quantifying the contributions to each impact category using scientific conversion factors, resulting in **midpoint indicators**. Midpoint indicators represent impacts at an intermediate point in the cause-effect chain, focusing on specific environmental problems (e.g., climate change measured in kg CO_2 equivalents). Optionally, midpoint results can be further aggregated into **endpoint indicators**, which reflect the impacts on areas of protection. *Finnveden et al. (2009)*.
- Interpretation: The final phase involves analyzing the results to draw conclusions and make recommendations aligned with the goal and scope of the study. This includes identifying significant environmental issues, evaluating the robustness of the results through sensitivity and uncertainty analyses, and considering the implications for decision-making *Finnveden et al. (2009)*.

Despite its widespread application, LCA has several limitations, including challenges related to data quality *Cooper and Kahn (2012)*, time and resource intensity, static analysis, and difficulties in accurately capturing the manufacturing phase *Reap et al. (2008b)*. Among these, one of the most critical issues is its static nature. As highlighted by *de Haes et al. (2004)*, LCA primarily functions as a steady-state tool, unable to account for dynamic changes in both environmental conditions and industrial processes. *Reap et al. (2008b)Reap et al. (2008a)* highlights this limitation, describing it as a moderately significant issue for the methodology, with current solutions being partially effective but still not fully addressing the problem. Although advancements have been made in incorporating temporal dynamics into LCA, existing methods often lack the flexibility needed to comprehensively capture the interactions between environmental and industrial systems *Levasseur et al. (2010)*. Also the studies that have integrated environmental considerations into manufacturing system design and operation *Duflou et al. (2012)*, most rely on static or only partially dynamic methods, limiting their ability to capture real-time changes in regulations, supply chains, or technology over extended product lifespans. As a result, they require periodic, manual updates of LCA data, which can be time-consuming and risk becoming obsolete. In this context, *Tukker (2000)* clarifies that there is no inherent conflict between Environmental Impact Assessment (EIA) and Life Cycle Assessment (LCA): while LCA is generally product-centric and focuses on detailed comparisons of alternative product systems, EIA addresses a broader set of assessments and emphasizes the organizational and decision-making processes surrounding an industrial activity. Despite defining system boundaries and impact assessments at different levels of detail, both methods share the same fundamental goal of evaluating the environmental implications of a subsystem.

Our exploration of the literature on Industry 4.0 models has identified various proposed architectures; however, none explicitly address the integration of sustainability aspects in a manner suitable for evaluating sustainable manufacturing processes *Garcés et al. (2021)*. This limitation underscores the need for a novel framework capable of dynamically integrating environmental considerations into industrial decision-making. To bridge this dual gap and enhance the effectiveness of environmental assessments, it is essential to leverage the untapped potential of interconnected architectures with external frameworks in a novel approach that combine the strengths of Industry 4.0 principles and robust environmental frameworks like Life Cycle Assessment (LCA), enabling a more dynamic and comprehensive analysis that takes advantage of the collective strengths of various systems *Kaiser et al. (2023)*. Among the several models and frameworks that have been proposed within the Industry 4.0 paradigm to structure interconnected and intelligent systems, the Reference Architecture Model for Industry 4.0 (RAMI 4.0) stands out due to its modularity, scalability, and well-defined structure, making it particularly suited for integration with new dimensions such as environmental sustainability *Melo et al. (2021)*.

RAMI 4.0 is organized along three primary axes, each designed to systematically represent and manage the complexities of modern industrial systems *DIN (2016)*. The “Lifecycle and Value Stream” axis captures the lifespan of a product or system, encompassing all phases from initial conception and design, to manufacturing and usage. The “Hierarchy” axis defines the various levels of control and responsibility within an organization, from field devices and control systems to enterprise management. By providing a clear delineation of roles and responsibilities, it ensures efficient communication and governance across all levels, from operational tasks to strategic decision-making. Lastly, the “Layers” axis represents the vertical decomposition of a system into different functional layers. This axis categorizes aspects of information technology and operational technology, dividing them into clear layers that range from physical devices up through to business processes and organizational requirements. This structured decomposition aids in managing the complexity of interconnected systems. To effectively incorporate sustainability considerations into manufacturing processes, we suggest introducing a new Environmental Assessment “EA” layer within RAMI 4.0 that facilitates communication with the LCA framework.

3. THE PROPOSED ENVIRONMENTAL ASSESSMENT LAYER

The introduction of the “EA” layer within the RAMI 4.0 framework (see Figure 2) is designed to interface with LCA, introducing a new dimension of analysis. The proposed additional layer is placed between the “Functional” and “Business” levels, in order to guarantee the transmission of information between adjacent levels, in accordance with the hierarchy principle that governs communication within RAMI 4.0 *DIN (2016)*. This layer is divided into two parts, corresponding to the “Type” and “Instance” portions of the “Lifecycle and Value Stream” axis.

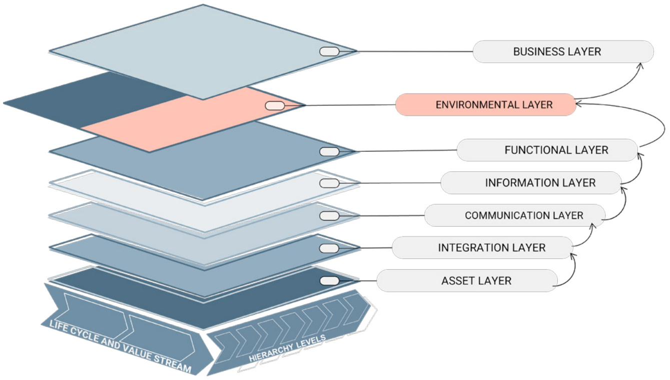

Fig. 2. *proposed additional ”EA” layer to the RAMI framework for integrating LCA*

In the “Type” phase, the design and planning of the asset lifecycle are analyzed, considering all the possible alternative production cycles of the product. This phase involves the evaluation of strategic decisions with medium-term impacts on materials, design, and production processes. The integration of the “EA” layer at this stage allows the simulation and prediction of the environmental impact of alternatives before they are implemented, providing the opportunity to optimize choices. In the “Instance” phase, corresponding to the operational phase where products or assets are already in production, the “EA” layer evaluates the implications of any changes in the current production cycle during production, without necessitating a complete overhaul of the product from the “Type” phase.

This layer’s functionality extends, also, across various hierarchical levels, ensuring that all the collected information is accessible and applicable at every decision-making level. For example, data gathered at the “Field Device” which involves direct input from machinery and sensors within the production environment, can be aggregated and utilized at higher levels, such as“Enterprise” or “Connected World”, for strategic decision-making purposes. In particular, the “Connected World” level facilitates the extension of interactions beyond company boundaries, utilizing data from supply chain to effectively involve the entire networks. This expansion of interactions enables the integration of environmental considerations that have often been overlooked in the past, such as transportation and other logistic issues, which significantly impact environmental assessments, providing a more comprehensive evaluation of the environmental footprint of a product. *Perotti et al. (2022)*

To illustrate the practical advantages of integrating the proposed ”EA” layer into the existing framework, consider an aerospace company that manufactures fuselage panels for commercial aircraft. Traditionally, these panels undergo a chemical milling process to achieve the desired thickness and structural properties. Because of the REACH regulations of the European Union (Registration, Evaluation, Authorization, and Restriction of Chemicals), which limit the use of certain chemicals, chemical milling is no longer the most environmentally viable option. To maintain the same product design, the company faces the challenge of modifying its production process to comply with new environmental regulations. The company decides to transition from chemical milling to mechanical milling.

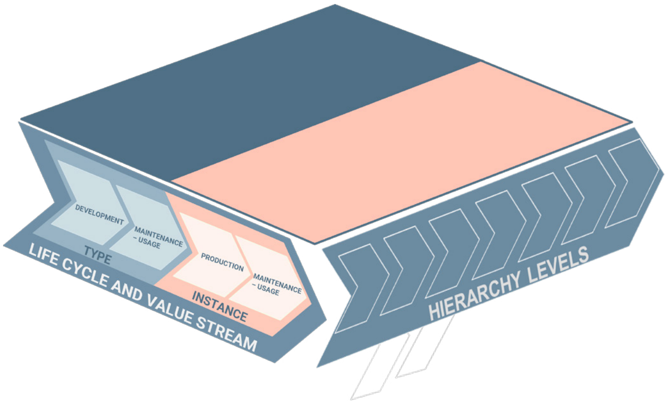

Fig. 3. *EA layer detail*

In the ”Type” phase the aerospace company’s engineering team is involved in the design and development of fuselage panels using traditional chemical milling processes. This phase involves setting specifications and choosing materials that meet the desired strength and weight requirements for commercial aircraft. By integrating the EA layer at this stage, the team can simulate various design scenarios and predict their environmental impacts before implementation. The EA layer provides quantitative assessments of factors like carbon emissions, energy consumption, and resource usage for each alternative. This quantitative assessment helps them understand the trade-offs between environmental impact and panel performance, guiding them to make informed decisions that align with both regulatory compliance and industry standards.

In the "Instance" phase, the company must continue producing fuselage panels without interruption. The EA layer plays a crucial role here, enabling the company to evaluate the environmental implications of transitioning from chemical to mechanical milling. This switch is not without challenges, as mechanical milling involves different processes that can impact both the environment and operational efficiency. Mechanical milling, for example, may significantly raise electricity usage. The EA layer could quantify this consumption and calculates the associated carbon emissions, providing data to ensure the company's operations align with sustainability targets. Waste management, also, emerges as another factor to consider. The metal shavings and chips generated by mechanical milling represent a significant waste management challenge. Here, the EA layer assesses the rates of waste generation and explores viable recycling or reuse options (see Figure 3). Using the considerations from the EA layer, the company is able to conduct a comprehensive comparison between chemical and mechanical milling, to maintain production efficiency and compliance with environmental regulations during the transition. Chemical milling offers advantages like uniform material removal and potentially lower immediate energy consumption but has significant disadvantages, including the use of chemicals, complex waste disposal requirements, higher environmental risk, and increased regulatory compliance costs. Mechanical milling eliminates chemicals and simplifies waste handling through metal recycling, improving worker safety. However, it may involve higher energy consumption, the need for investment in new machinery, and possible changes in production throughput. From the RAMI 4.0 framework perspective, the inclusion of the EA layer tackles complexities that existing layers do not manage. While the "Functional" level concentrates on operational processes the EA layer enriches this level by collecting and processing real-time data from sensors on milling machines, capturing metrics such as energy consumption, emissions, and waste generation. The insights generated at the "Functional" level are then aggregated and analyzed to inform the "Business" level, where strategic decisions are made. By employing Multi-Criteria Decision Analysis (MCDA) *Zanghelini et al. (2018)*, the EA layer translates these operational data points into actionable insights.

In conclusion the EA layer acts as a bridge, embedding environmental considerations into every level of the RAMI 4.0 framework. By integrating real-time data collection and advanced analytical tools it transforms raw operational data into actionable insights that support both immediate process optimizations and long-term strategic decisions.

4. CONCLUSION AND FUTURE WORKS

In the evolving context of Industry 4.0, the imperative to integrate sustainability into manufacturing processes has transitioned from an option to a necessity. This paper introduces an enhancement to the RAMI 4.0 model by integrating an Environmental Assessment (EA) layer, addressing critical gaps in the existing framework. This new layer is designed to automate the collection and analysis of environmental data, minimizing reliance on manual intervention, expert judgment, and assumptions at various stages, to embed environmental considerations at every decision-making level, both operational and strategic. By automating data collection and integrating advanced processing models, this EA layer overcomes the limitations of traditional static LCA methodologies, transforming environmental assessments from static and manual processes into dynamic, automated systems. This transformation enables companies to proactively manage their environmental impacts, making sustainability an integral part of their operations and strategic planning. The case of the aerospace company transitioning from chemical to mechanical milling illustrates the practical benefits of the EA layer within the RAMI 4.0 architecture. Without altering product design or chemical composition, the company modifies its production process to meet stringent environmental regulations and enhance sustainability. The EA layer proves essential for process transition management, evaluating and optimizing new production methods in response to regulatory changes or market demands. It promotes sustainability by embedding environmental assessments into daily operations and long-term strategic planning, ensuring that the company remains competitive by quickly adapting to changes while demonstrating a commitment to sustainable practices valued by customers and stakeholders. To ensure the effective implementation of this layer with the external LCA framework requires the establishment of communication protocols and data exchange processes, that enables continuous, bidirectional communication, maintaining a coherent flow of environmental data for both strategic evaluations and operational decisions.

This integration is supported by the future development of interfaces, like Application Programming Interfaces (APIs), to facilitate the dynamic integration of external LCA software tools within the existing RAMI 4.0 architecture. APIs serve as connectors, enabling the real-time exchange of environmental data collected at the production floor and processed by dedicated LCA platforms. Specifically, APIs retrieve operational data automatically from sensors and smart devices at the Asset Layer, then this data are transferred to external LCA software at the Environmental Layer, allowing continuous updates of environmental impact metrics without manual data entry. The processed LCA results are returned to the Functional Layer, making these insights immediately accessible for operational decision-making and process optimization. APIs also facilitate the integration of aggregated LCA data into the Business Layer, supporting strategic sustainability planning and reporting. To enable such integration, it is advisable to adopt recognized standards such as RESTful APIs *Fielding (2000)*, JSON *Crockford and Morningstar (2017)* or XML data formats *Textuality (2000)*, and protocols like OPC UA *Morgan and O'Donnell (2018)*, which are tailored to the Industry 4.0 environment. RESTful APIs, in particular, enable standardized interactions between different software applications, facilitating interoperability and flexibility. JSON and XML provide structured, standardized formats for clear, efficient data transmission, while MQTT and OPC UA protocols ensure secure and reliable data exchange, particularly suited to real-time operational contexts. This bidirectional, real-time communication reduces human error and manual activities, enabling proactive environmental management aligned with operational needs and regulatory compliance. The aerospace company's case study, transitioning from chemical to mechanical milling, illustrates practical benefits: without altering product design or chemical composition, the company effectively adjusts its manufacturing process to comply with stringent environmental standards, guided by continuously updated environmental impact assessments. Automating these processes reduces manual intervention and the risk of human error, nevertheless, despite automation enhancements, the reliance on expert judgment cannot be entirely eliminated. To strengthen the effectiveness of this model, additional research is needed to test and validate this dynamic EA layer across diverse industrial scenarios to confirm its adaptability, scalability, and efficacy. Expanding empirical investigations will further validate this approach's potential to embed sustainability seamlessly into Industry 4.0 frameworks and foster robust, environmentally responsible manufacturing practices.

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