Prospects of Digital Twin for Dynamic Life Cycle Assessment of Smart Manufacturing Systems

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Abstract. Smart manufacturing systems are poised to revolutionize industrial processes by leveraging advanced technologies for increased efficiency and productivity. However, alongside these advancements, there is a growing imperative to address environmental sustainability concerns. Conventional static life cycle assessment (LCA) methods often provide valuable insights into the environmental impacts of such manufacturing systems but often fall short in capturing real-time data and dynamic system interactions. Further, using the digital twin technology, physical assets can be virtually replicated in order to monitor, evaluate, and improve the particular manufacturing system. The dynamic properties can be effectively brought to LCA investigations by utilizing this technique. This paper explores the prospects of integrating digital twin technology for facilitating the dynamic LCA to enable comprehensive and timely environmental performance evaluation of smart manufacturing systems. We discuss the concepts, technological components, and potential applications of digital twin-enabled dynamic LCA, along with challenges and future research directions.

1 Introduction

Smart manufacturing systems, which use cutting-edge technology to maximise output, stimulate innovation, and optimise efficiency, represent a paradigm shift in industrial operations. Real-time data collecting, predictive analytics, and production process automation are made possible by smart manufacturing systems, which integrate cutting-edge technologies like IoT, AI, robotics, and big data analytics [1]. This transition lowers environmental impact, streamlines resource utilisation, and enhances quality control and customisation capabilities. Smart manufacturing has a significant impact on energy optimisation, predictive maintenance, and responsive production scheduling [2]. However, since smart manufacturing is a new paradigm in production, its effects on society and the environment are unclear and require further consideration [3]. Life-Cycle Assessment (LCA) is a methodology used to assess the environmental impact associated with all stages of a product's life cycle from cradle-to-grave as depicted in figure 1.

Conventional Life Cycle Assessment (LCA) techniques are methodical ways to assess how a process, good, or service affects the environment from the extraction of raw materials to their disposal. However, the ability of conventional LCA approaches to perform accurate and thorough environmental impact assessments may be hampered by their inability to capture real-time data and dynamic system interactions [4]. These techniques frequently rely on presumptions about system behaviour and static data, which might not accurately represent the dynamic character of contemporary manufacturing processes/ system. Furthermore, real-time monitoring of environmental parameters, such as energy use,

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emissions, and waste generation, which can change dramatically over time, is usually not possible with such static LCAs [5]. Moreover, the failure to consider dynamic system interactions such as feedback loops and nonlinear relationships can result in assessments that are overly simplistic and fail to adequately convey the complexity of the situation. Hence, it is important to take the temporal fluctuations and dynamic interactions of manufacturing system into considerations. Dynamic methodologies, as opposed to static LCAs, can reflect how environmental effects change over time as a result of modifications to consumer behaviour, technology, production processes, and other process variables [6].

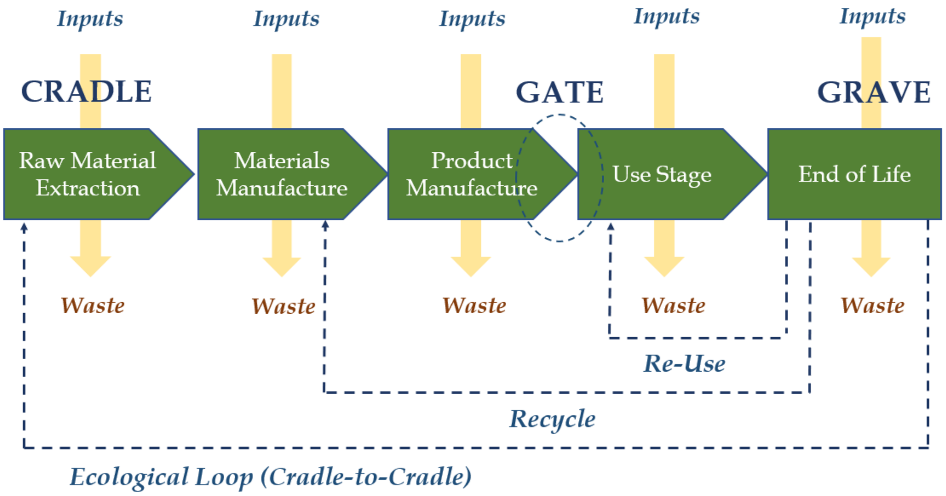

Fig. 1. Life Cycle Assessment (LCA) Stages

Digital twin technology, which creates virtual replicas of real assets and processes and provides a number of advantages like real-time monitoring, predictive maintenance, and scenario modelling, is essential to smart manufacturing. Manufacturers may enhance overall productivity, optimise production processes, and obtain deeper insights into their operations with the help of digital twins. In this paper, we propose leveraging digital twin technology to enable dynamic LCA, thereby enhancing environmental sustainability assessment in smart manufacturing systems. Integrating Digital Twins (DT) for dynamic Life Cycle Assessment (LCA) can help opens avenues for sustainable and environmentally friendly smart manufacturing system.

2 Concept of Digital Twin (DT) and Dynamic Life Cycle Assessment (DLCA): DT is a digital duplication of entities with real-time two-way communication enabled between the cyber and physical spaces [7]. DT technology is an effective tool to fulfil the requirements of smart manufacturing by reflecting the physical status of systems in a virtual space. Digital twin technology revolutionizes how physical assets, processes, or systems are replicated in the digital realm, offering highly detailed and accurate virtual representations that mirror real-world counterparts in behaviour, performance, and interactions. In essence, digital twin technology's pivotal role in simulating real-world systems through virtual representations, predictive analytics, simulation capabilities, remote monitoring, and lifecycle management functionalities offers unprecedented opportunities for innovation, optimization, and sustainability across industries and applications. Fig. 2 depicts the typical architecture of the Digital Twin for digital production [8].

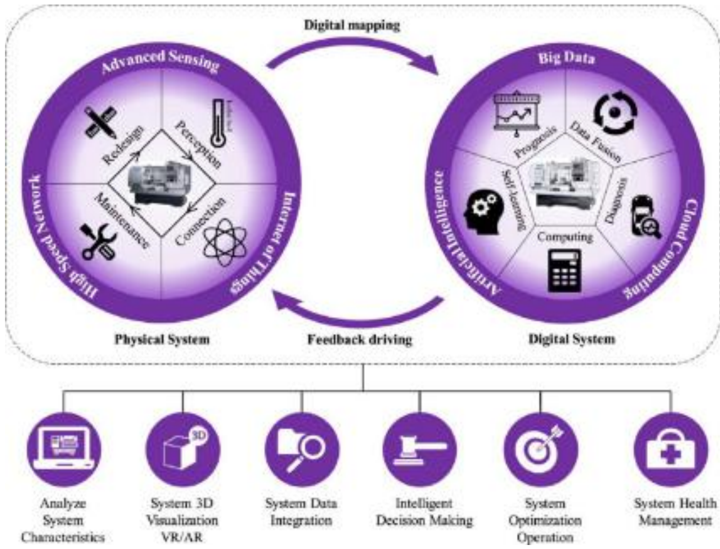

Fig. 2. The design of the digital twin for manufacturing [8]

On the other hand, a dynamic LCA (DLCA) is an approach used to improve the accuracy of LCA by addressing the inconsistency of temporal assessment [9]. As an advanced methodology that incorporates temporal fluctuations and dynamic interactions into environmental impact evaluations across a product's lifecycle, DLCA offers an alternative to static LCA, which takes a single snapshot approach to environmental performance. DLCA is especially relevant in the context of smart manufacturing since it is in line with adaptive manufacturing processes that are fuelled by automation, artificial intelligence, and smart IoT. By evaluating environmental implications in real-time, this approach facilitates adaptive decision-making to maximise environmental performance. Furthermore, DLCA leverages real-time data produced by intelligent manufacturing systems to support continuous improvement by uninterruptedly evaluating environmental effects over time [10]. DLCA can provide a lifecycle perspective that enable manufacturers to understand the whole environmental impact of their processes and products. This enables them to make well-informed decisions to reduce their environmental impact. Figure 3 demonstrates the typical LCA framework.

3 Integration of digital twins for dynamic Life Cycle Assessment (DLCA):

Digital twins construct virtual representations of physical entities, capturing real-time data and interactions to furnish comprehensive insights. Manufacturers can advance sustainability by employing digital twins for carrying out the dynamic lifecycle assessments, thereby gaining profound insights into environmental consequences throughout a product's lifespan. These methodologies, analogous to those employed in other manufacturing systems such as ERP and MES, enable the integration of technologies for accessing LCA, as illustrated in figure 4 [11]. This union yields benefit like real-time data synchronization, facilitating precise assessments and timely interventions to optimize the resources. Moreover, the integration of digital twins for dynamic life cycle assessment has the potential to enhance resource efficiency, reduce environmental effects, and stimulate sustainable innovation.

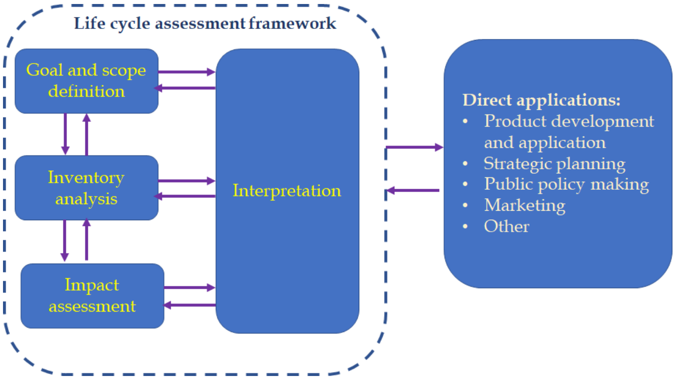

Fig. 3. LCA framework [3]

3.1 Technological components essential for dynamic LCA: The technological components necessary for dynamic Life Cycle Assessment (LCA) in smart manufacturing systems may include modeling frameworks, sensor networks, cloud computing infrastructure, data acquisition systems, Internet of Things (IoT) devices, simulation software, LCA software, and modeling frameworks. IoT devices incorporate data into LCA models for decision-making, while sensor networks gather real-time data on environmental conditions. Data collected by sensors can be processed by data collection systems. Digital twins are created for scenario analysis using simulation software, and theoretical foundations are provided by modeling frameworks. Together, these elements enable detailed assessment of environmental performance through digital twin-driven techniques and facilitate sustainable innovation in smart manufacturing.

3.2 Integration methods to combine digital twins for dynamic LCA: Digital twin integration for dynamic Life Cycle Assessment requires careful consideration of modeling approaches, interoperability, and data interchange. This process can be supported by various integration techniques, such as developing uniform data formats and protocols for seamless data interchange, coupling digital twin models with dynamic simulation models, utilizing simulation-based analysis for comprehensive assessment, applying data-driven modeling techniques for predictive insights, integrating digital twin platforms with LCA software solutions, and establishing standards and guidelines to ensure consistency and reproducibility. Moreover, this integration demands a multidisciplinary strategy that combines expertise in data science, modeling, simulation, and sustainability assessment. Such an approach facilitates the integration of smart manufacturing systems with thorough environmental performance evaluation. Consequently, manufacturers can achieve comprehensive environmental performance evaluation and promote sustainable practices throughout their operations by integrating digital twins for dynamic LCA.

3.3 Challenges and Opportunities: In order to effectively assess the environmental impact of smart manufacturing, a number of issues related to the integration of data from digital twins with dynamic models must be resolved. First, trustworthy evaluations depend on the accuracy and consistency of real-time data gathered from sensors, Internet of Things (IoT) devices, and industrial processes. Furthermore, effective computational resources are needed to manage the scalability and complexity of dynamic models and digital twins, particularly for large-scale simulations or scenario studies. Standards and interoperability are essential for enabling smooth model integration and data interchange between various software tools and platforms. To provide a smooth integration process, it is imperative to establish standardised data formats and protocols for digital twin platforms and the LCA software to ensure technical compatibility and interoperability. Furthermore, in order to examine the robustness of effect assessments and capture temporal fluctuations, dynamic modelling approaches and uncertainty analysis are crucial. By employing integrated digital twins in conjunction with dynamic LCA approaches, organisations will be able to conduct comprehensive environmental performance evaluation in smart manufacturing systems by overcoming these obstacles through a multidisciplinary approach.

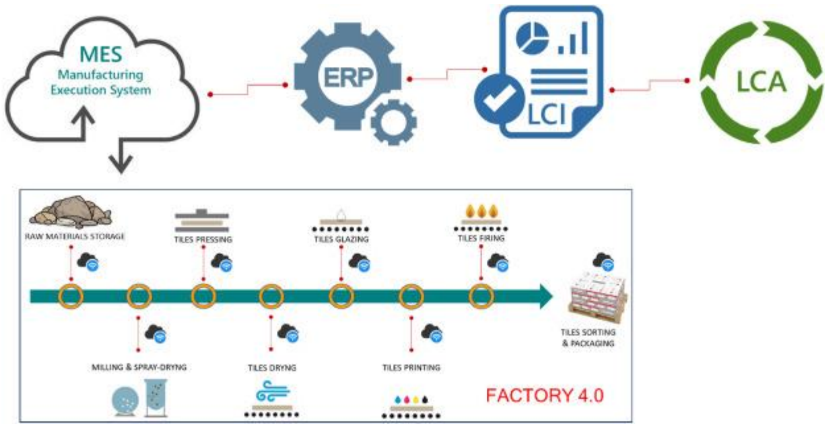

Fig. 4. Conceptual Pattern of the Dynamic LCA system [11]

3.4 Future research direction: Future research and development in the integration of digital twins for Dynamic LCA can focus on many important directions to advance the field and capitalise on new opportunities and difficulties. Creating multi-scale and multi-domain modelling tools to capture interactions across various levels of manufacturing systems is one of these. Another is enhancing data integration and analytics by utilising advanced methods like predictive analytics and semantic interoperability. Further, the product lifecycle management can be optimised by integrating sustainable design and circular economy principles, and the robustness of environmental effect evaluations can be assessed using dynamic uncertainty quantification tools. Long-term monitoring and adaptive management frameworks can facilitate ongoing improvements in sustainability performance. Additionally, socio-technical systems perspectives can help consider the broader implications of sustainability. By taking these steps, the understanding of the environmental effects of smart manufacturing can be enhanced.

4 Concluding remarks

Enhancements and breakthroughs in sustainable practices for smart manufacturing can lead to notable gains in resilience, resource efficiency, and environmental performance. A number of potential innovations include closed-loop supply chains that support circular economy concepts, digital twin-based material lifecycle assessments for sustainable material selection, and digital twins for energy-efficient manufacturing processes. The integration of digital twins for dynamic LCA methodologies and the development of collaborative sustainability platforms that facilitate stakeholder collaboration to co-create new solutions are critical improvements in lifecycle sustainability assessment tools. It draws attention to the possibility of using dynamic modelling tools with real-time data from digital twins to evaluate environmental performance of smart manufacturing system in a comprehensive way. But there are a number of issues that need to be considered, such as stakeholder participation, uncertainty measurement, and technical complexity of the manufacturing system. In addition to creating standards and interoperability frameworks, future research and development initiatives should concentrate on improving data integration, multi-scale modelling, and stakeholder engagement. Furthermore, there is hope that future developments and breakthroughs in smart manufacturing sustainability practices, like the use of sustainable materials and energy-efficient procedures, would result in notable gains in resource efficiency and environmental performance. Organisations can effectively utilise digital twin technologies to generate resilient and sustainable innovation in manufacturing operations by embracing this integration and addressing related hurdles. There is significant potential for revolutionizing environmental performance evaluation in smart manufacturing systems and paving the way for a more sustainable future. This can be achieved through the integration of digital twin technologies for dynamic life cycle assessment.

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