Circular Lean–Six Sigma 4.0: A Framework for Sustainable Manufacturing and Operational Resilience

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Abstract- The Circular Lean–Six Sigma 4.0 (CLSS 4.0) framework represents a novel approach to sustainable manufacturing by integrating Lean principles, Six Sigma methodologies, and circular economy strategies under the enabling infrastructure of Industry 4.0 technologies. This model extends beyond traditional efficiency and quality improvement, positioning waste not only as inefficiency but also as a loss of resources that could be reintegrated into value chains. By combining Lean's focus on eliminating non-value-adding activities, Six Sigma's data-driven methods for reducing variability, and circular practices such as remanufacturing and resource recovery, CLSS 4.0 creates a foundation for operational resilience and ecological sustainability. Industry 4.0 tools, including IoT, artificial intelligence, and blockchain, enhance this integration by enabling real-time monitoring, predictive analytics, and trusted data sharing across supply chains. The findings highlight that CLSS 4.0 can simultaneously deliver cost efficiency, resource preservation, and long-term competitiveness, offering a holistic framework for industries aiming to align operational excellence with sustainability and resilience goals.

Index Terms- Circular Lean Six Sigma; CLSS 4.0; Sustainable Manufacturing; Operational Resilience; Industry 4.0; Circular Economy; Lean Management; Six Sigma; Process Improvement; Digital Transformation.

I. INTRODUCTION

The convergence of sustainability imperatives with advanced management methodologies has created the need for integrated frameworks that go beyond efficiency to embrace resilience, adaptability, and resource circularity. Traditional Lean and Six Sigma approaches have long been recognized for their ability to reduce waste and variability while increasing productivity and quality (Womack & Jones, 2003; Antony, 2006). However, in the context of the circular economy, where resource recovery, remanufacturing, and closed-loop supply chains are central, these approaches require adaptation. The proposed Circular Lean–Six Sigma 4.0 (CLSS 4.0) model integrates Lean, Six Sigma, and circular economy principles, reinforced by digital technologies of Industry 4.0, to create a comprehensive framework for sustainable manufacturing. This model not only seeks efficiency but also aligns operational excellence with long-term ecological and economic sustainability.

At its core, CLSS 4.0 builds on Lean's philosophy of eliminating non-value-adding activities and Six Sigma's rigorous focus on reducing variability and defects (George, 2002; Antony et al., 2017). In a circular context, waste is not merely conceptualized as inefficiency but as a loss of materials that could otherwise remain within productive cycles. For example, overproduction, defects, and excess inventory are recast as missed opportunities to preserve resources through reuse, repair, or remanufacture. Six Sigma's data-driven DMAIC (Define–Measure–Analyze–Improve–Control) methodology is repurposed to not only improve process capability but also to incorporate circular KPIs such as value retention efficiency, recirculation rate, and carbon footprint reduction (Mitra, 2016; Jabbour et al., 2018). By embedding circular performance metrics within Lean–Six Sigma routines, organizations are encouraged to pursue environmental and social goals alongside operational excellence.

The "4.0" dimension of the CLSS model emphasizes the role of digital transformation in scaling these synergies. Industry 4.0 technologies such as the Internet of Things (IoT), cyber-physical systems, artificial intelligence, and digital twins enhance the observability, controllability, and traceability of manufacturing systems (Lee et al., 2015; Xu et al., 2018). IoT-enabled sensors provide real-time data on machine utilization, energy consumption, and material flow, while advanced analytics identify hidden sources of inefficiency and opportunities for resource recovery. AI models complement Six Sigma by detecting process anomalies, predicting defect occurrence, and simulating process improvements under circular constraints. Meanwhile, blockchain can provide immutable product passports, enabling traceability across supply chains and facilitating closed-loop logistics (Saberi et al., 2019; Kristoffersen et al., 2020). These technologies empower manufacturers to integrate Lean–Six Sigma tools with circular economy strategies in ways that were previously infeasible.

Case study evidence suggests that when Lean and Six Sigma principles are reframed within a circular lens, firms can simultaneously achieve cost reduction and environmental gains. For instance, applying value-stream mapping to track not only process waste but also material losses across product life cycles reveals new opportunities for component reuse and material recovery (Lieder & Rashid, 2016). Similarly, design of experiments (DOE), traditionally used for process optimization, can be adapted to assess durability, reparability, and recyclability in product design. The incorporation of predictive analytics enhances the DMAIC cycle by enabling proactive interventions rather than reactive controls, aligning with the resilience objectives of circular systems (Pagoropoulos et al., 2017; Bag et al., 2020).

An important feature of CLSS 4.0 is its systemic orientation. Lean and Six Sigma are often applied within factory boundaries, but circularity requires extending their scope to the entire value chain. Reverse logistics, remanufacturing networks, and recycling ecosystems must be coordinated with upstream suppliers and downstream customers. Here, Six Sigma's emphasis on stakeholder voice and Lean's collaborative practices provide the governance tools needed to align incentives and integrate multiparty processes (Jabbour et al., 2019). By leveraging blockchain for data integrity and digital twins for cross-organizational modeling, CLSS 4.0 supports resilience by ensuring that disruptions, material shortages, or regulatory changes can be anticipated and mitigated in real time.

The model also emphasizes organizational culture. The Lean philosophy of continuous improvement (Kaizen) is extended to embrace "continuous circularity," where improvement projects explicitly target resource loops and eco-efficiency. Employee involvement in waste identification, standardization of circular practices, and cross-functional training are key enablers of CLSS 4.0 (Antony et al., 2017; Jabbour et al., 2018). Furthermore, leadership commitment and alignment with corporate sustainability strategies are essential for ensuring that Lean–Six Sigma projects are not short-term efficiency exercises but long-term drivers of resilience and competitiveness.

Despite its promise, the implementation of CLSS 4.0 faces challenges. Firms may struggle with aligning traditional Lean–Six Sigma metrics with circular economy indicators, especially where short-term cost pressures dominate. Data integration across heterogeneous digital platforms, concerns about data privacy, and the need for skilled personnel in both analytics and sustainability present additional barriers (Xu et al., 2018; Kristoffersen et al., 2020). Nonetheless, early adopters demonstrate that these challenges can be overcome through incremental deployment, starting with pilot projects that incorporate IoT-based monitoring into existing Lean–Six Sigma programs and gradually extending to supply chain–wide initiatives.

The flowchart illustrates the structure of the Circular Lean–Six Sigma 4.0 (CLSS 4.0) framework, showing how traditional Lean and Six Sigma principles evolve when integrated with circular economy concepts and Industry 4.0 technologies. It begins with Lean's focus on eliminating non-value activities and Six Sigma's emphasis on reducing variability through the DMAIC methodology. These foundations are then reframed within a circular lens, where waste is understood as material loss and performance is measured with circular KPIs such as recirculation rate and value-retention efficiency. Industry 4.0 enablers—including IoT, AI, digital twins, and blockchain—provide the digital infrastructure for real-time monitoring, predictive analytics, and supply chain traceability. The model also highlights the role of organizational culture, extending Kaizen into "continuous circularity" supported by employee engagement and leadership commitment. Together, these elements converge to deliver outcomes that align operational excellence with sustainability, enabling closed-loop, resilient, and eco-efficient production systems.

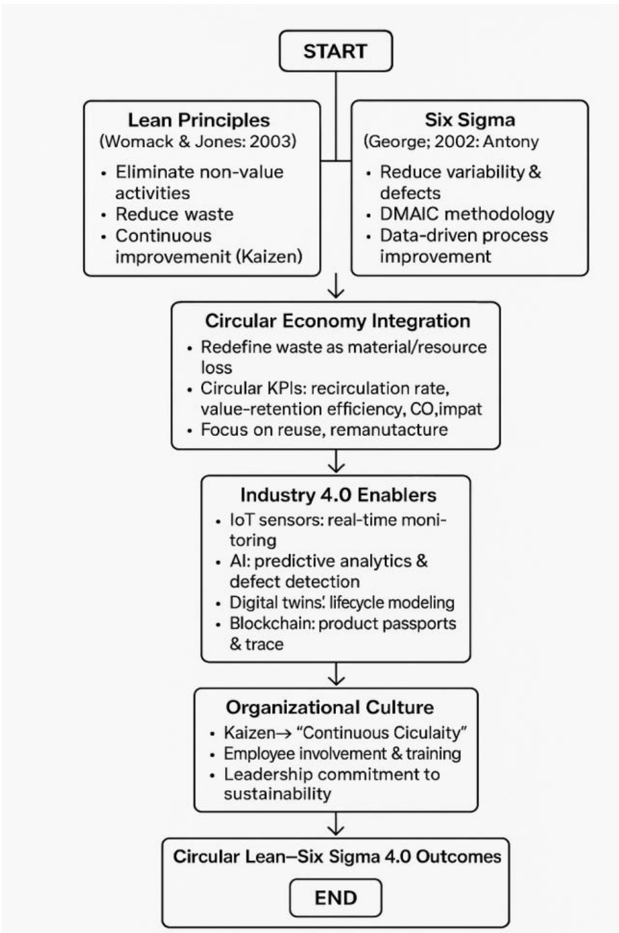

Figure 1. Circular Lean–Six Sigma 4.0 (CLSS 4.0) Framework.

Source: Created by author.

In conclusion, CLSS 4.0 provides a robust framework that unites operational excellence with circular economy principles under the enabling infrastructure of Industry 4.0. By combining Lean's waste elimination, Six Sigma's data-driven rigor, and digital technologies' capacity for real-time adaptation, the model creates a pathway for manufacturers to achieve both efficiency and resilience. It supports the development of closed-loop production systems that are not only environmentally sustainable but also economically competitive. As manufacturing industries face mounting pressures from resource scarcity, climate change, and global competition, CLSS 4.0 offers a holistic, actionable approach to aligning process improvement with sustainability goals, thereby contributing to the evolution of truly sustainable and resilient industrial ecosystems.

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