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LOW-FRICTION DESIGN FOR ENERGY REDUCTION IN CIRCULAR MANUFACTURING PROCESSES

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ABSTRACT

This article explores the role of low-friction design as a strategic tool for reducing energy consumption within circular manufacturing systems. While circular economy models typically emphasize recycling, remanufacturing, and material efficiency, the minimization of physical and operational friction has received limited attention. Drawing from tribology and lean manufacturing literature, the study highlights how advanced coatings, lubricants, optimized surfaces, and novel materials can reduce mechanical resistance, while digital tools such as IoT, blockchain, and AI can streamline workflows to eliminate operational inefficiencies. The analysis suggests that integrating low-friction strategies into circular manufacturing may reduce energy consumption by up to 40%, extend equipment lifecycles, and enhance process resilience. The article concludes that bridging tribology with circular economy research is essential to achieving truly energy-efficient and sustainable production systems.

Keywords: Circular economy. Low-friction design. Tribology. Energy efficiency. Sustainable manufacturing. Operational efficiency. IoT. Blockchain.

INTRODUCTION

The pursuit of circular economy models has focused heavily on recycling, remanufacturing, and material efficiency, but less attention has been given to the role of design strategies that directly reduce energy demand in production systems. One promising yet underexplored avenue is low-friction design, which seeks to minimize resistance—both physical and operational—within circular manufacturing environments. By reducing energy losses caused by mechanical friction in equipment as well as systemic inefficiencies in processes, low-friction design can yield significant sustainability gains. Emerging research suggests that such approaches may lower energy consumption in industrial contexts by up to 40%, positioning them as a critical but overlooked lever for enhancing the performance of circular factories (Holmberg & Erdemir, 2017).

Physical friction is a fundamental source of energy inefficiency in manufacturing systems. Tribological studies demonstrate that approximately 20–30% of the world's total energy consumption is linked to mechanical friction and wear in moving components (Holmberg & Erdemir, 2019). Techniques such as the use of advanced coatings, low-viscosity lubricants, optimized surface topographies, and novel materials can drastically reduce these losses. In a circular manufacturing context, this is particularly relevant as machinery is often used for extended lifecycles, refurbished, or adapted for processing secondary materials. Designing equipment with low-friction interfaces not only improves energy efficiency but also extends component durability, thereby reducing material waste and maintenance costs (Nosonovsky & Bhushan, 2013).

Beyond the physical dimension, operational friction—defined as inefficiencies and bottlenecks in industrial workflows—also consumes significant energy. In factories implementing circular practices such as disassembly, remanufacturing, and recycling, operational friction can manifest in the form of slow information flows, misaligned scheduling, and poorly integrated logistics. Lean manufacturing literature highlights that such inefficiencies not only delay processes but also result in unnecessary energy use through idle machines, repeated handling, and non-optimal routing of materials (Womack & Jones, 2003). Digital tools such as IoT-enabled monitoring, blockchain-based coordination, and AI-driven scheduling can mitigate these operational barriers, reducing the hidden energy footprint of circular production.

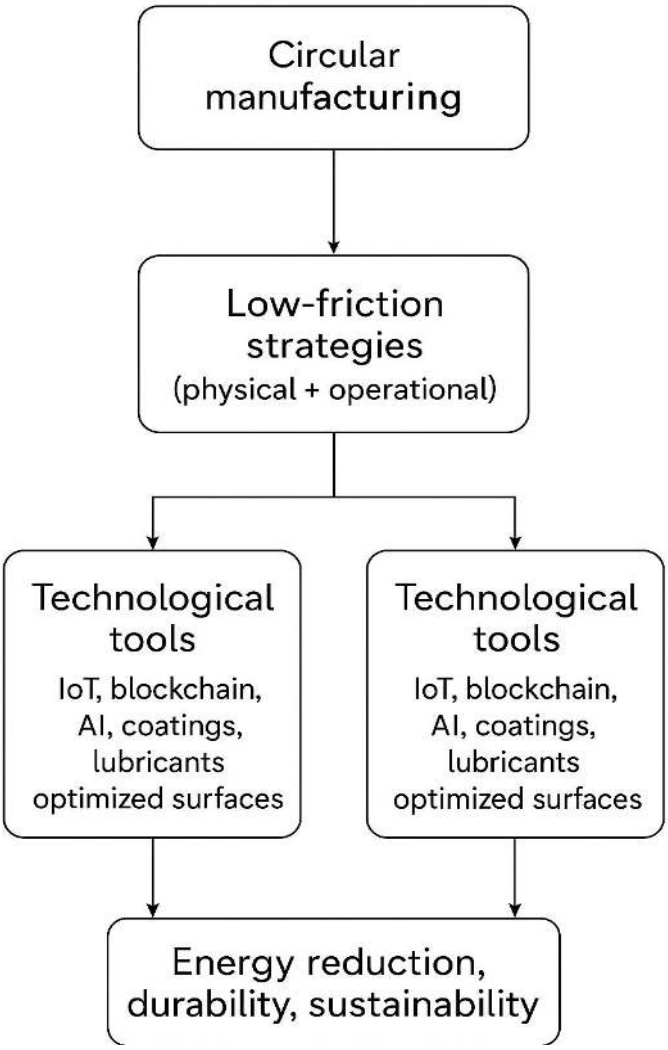
The integration of low-friction design into circular economy strategies thus requires a dual focus. At the micro-level, tribological innovations must be embedded in machine components, ensuring that every unit of input energy is converted into productive work with minimal resistance. At the macro-level, organizational design must streamline the flow of materials and information, reducing energy wasted through delays and redundancies. For example, predictive maintenance supported by IoT can prevent excessive frictional losses in bearings and gears, while blockchain-secured data sharing across supply chains can lower coordination costs and operational energy overheads. When combined, these approaches enable factories not only to recycle and reuse materials more efficiently but also to operate with substantially lower energy intensity.

Despite the clear potential, the academic literature has only begun to address the systemic role of low-friction design in circular manufacturing. Tribology research often focuses narrowly on mechanical performance, while circular economy studies emphasize material flows and waste reduction rather than energy efficiency through friction minimization. Bridging these domains is necessary to create comprehensive frameworks that link design, sustainability, and energy performance. Furthermore, empirical studies quantifying the energy savings of low-friction approaches in real-world circular factories remain scarce. Initial estimates suggest potential reductions of up to 40% when optimized across both physical and operational dimensions, but robust evidence from large-scale applications is needed (Holmberg & Erdemir, 2017).

The flowchart illustrates how circular manufacturing integrates low-friction strategies to enhance energy efficiency and sustainability. At its core, the model emphasizes reducing both physical friction in machinery and operational inefficiencies in workflows. These strategies are supported by technological tools such as IoT, blockchain, AI, advanced coatings, lubricants, and optimized surfaces, which work together to minimize resistance and streamline processes. The ultimate outcome is significant energy reduction, extended equipment durability, and improved overall sustainability, highlighting the importance of bridging tribology with digital innovation in circular economy systems.

Figure 1

Integration of Low-Friction Design Strategies in Circular Manufacturing



Source: Created by author.

In conclusion, low-friction design represents a critical but underutilized strategy for advancing circular economy objectives. By simultaneously reducing physical resistance in machinery and operational inefficiencies in workflows, industries can achieve substantial energy savings while enhancing equipment longevity and process resilience. Integrating tribological advances with digital tools such as IoT, AI, and blockchain offers a pathway toward high-efficiency, low-waste circular factories. Future research should focus on interdisciplinary frameworks that combine engineering, process optimization, and organizational design, ensuring that the next generation of circular manufacturing is not only material-efficient but also energy-efficient at its core.

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