

Advancing sustainable manufacturing: A critical review of CAD/CAM integration in eco-conscious product design

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Structured Abstract

Background: Sustainable product design aims to minimize environmental impact while optimizing resource efficiency and lifecycle performance. Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) technologies are pivotal in achieving these goals by enabling virtual prototyping, material optimization, and waste reduction. However, challenges such as high implementation costs, software limitations, and insufficient training hinder their adoption, particularly among small and medium-sized enterprises (SMEs). This study critically examines the role of CAD/CAM tools in sustainable design, focusing on their ability to integrate frameworks like Life Cycle Assessment (LCA) and Circular Economy (CE) principles, while addressing barriers to widespread implementation.

Literature Review: CAD/CAM technologies are pivotal for advancing sustainable product design by enabling material optimization, waste reduction, and lifecycle analysis. Tools like SolidWorks and AutoCAD integrate frameworks such as Life Cycle Assessment (LCA) and Circular Economy (CE) principles, supporting eco-friendly material selection and modular designs for repair and recycling. However, challenges persist, including software limitations in handling complex geometries, high costs for SMEs, and insufficient training. Emerging solutions like cloud-based platforms and AI-driven predictive design offer cost-effective pathways, though compatibility with existing workflows remains underexplored. Critical gaps include quantifying CAD/CAM's direct impact on sustainability metrics and strategies to address data inaccuracies, underscoring the need for cross-industry collaboration to scale circular practices.

Conclusion: CAD/CAM technologies offer transformative potential for sustainable manufacturing but require strategic interventions to overcome current limitations. Key recommendations include enhancing data accuracy, adopting scalable solutions for SMEs, and leveraging AI-driven tools for predictive design optimization. The study emphasizes the importance of aligning CAD/CAM workflows with global sustainability frameworks like the UN SDGs and CE principles. By addressing these challenges, industries can harness CAD/CAM's full potential to drive eco-friendly innovation, reduce waste, and achieve long-term economic and environmental resilience.

Keywords: Sustainable Product Design, CAD/CAM Technologies, Circular Economy, Life Cycle Assessment (LCA), Industry 4.0

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