Sustainable Product Design for Disassembly: Integrating Digital Thread and Lifecycle Assessment (LCA) Tools

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Abstract

The transition to a Circular Economy (CE) necessitates a fundamental shift in product design from traditional end-of-life disposal to strategies that facilitate reuse, remanufacturing, and recycling. Design for Disassembly (DfD) is a critical enabler of this transition [1, 2]. However, its effective implementation is often hindered by fragmented information flows across the product lifecycle and a lack of integrated sustainability assessment during early design stages [3,4]. This paper proposes a novel, integrated framework that merges the Digital Thread-a seamless, data-driven continuum of information from design to end-of-life [5] with Lifecycle Assessment (LCA) tools to empower Sustainable Product Design for Disassembly. The Digital Thread ensures real-time access to critical data such as material specifications, joinery methods, assembly sequences, and bill of materials, feeding directly into LCA software for dynamic environmental impact evaluation [6]. This integration allows designers to conduct instantaneous "what-if" analyses, quantifying the environmental and economic trade-offs of different disassembly strategies. A conceptual case study of an electric motor is presented to illustrate the framework's application. The study demonstrates how the system can optimize design choices such as selecting snap-fits over chemical adhesives or standardizing fasteners by visualizing their impact on disassembly time, component purity for recycling, and overall carbon footprint [7, 8]. The proposed framework addresses significant sub-themes of the conference, including *Technology, AI & Sustainability* through data integration, *Sustainable Management Practices* via improved decision-making, and *Future Challenges & Innovations* in circular economy implementation. This research concludes that the synergy of Digital Thread and LCA is pivotal for transitioning DfD from a qualitative guideline to a quantifiable, optimized, and digitally-enabled standard practice in 21st-century sustainable manufacturing [9, 10].

Keywords: Design for Disassembly (DfD), Digital Thread, Lifecycle Assessment (LCA), Circular Economy, Sustainable Manufacturing, Digital Transformation.

1. Introduction

The linear "take-make-dispose" industrial model is ecologically untenable [11]. The concept of a Circular Economy (CE) offers a regenerative alternative, aiming to retain product value and materials within the economy for as long as possible [12]. A critical barrier to achieving CE is product design; most products are not designed with their end-of-life or subsequent lifecycles in mind [13]. Design for Disassembly (DfD) is a proactive design philosophy that considers the ease and cost of separating a product into its constituent parts and materials at the end of its useful life, thereby enabling repair, refurbishment, remanufacturing, and high-quality recycling [1, 2].

Despite its recognized importance, DfD faces two major implementation challenges:

1) Information Silos: Critical design and manufacturing data (e.g., precise material grades, adhesive types, assembly sequences) are often locked in disparate systems (CAD, PLM, ERP), inaccessible for end-of-life planning [3].

2) Late-Stage Assessment: Traditional LCA is often conducted post-design, missing the opportunity to inform critical early-stage decisions where 80% of a product's environmental impact is determined [4].

Digital Transformation, particularly through the Digital Thread a unified, data-driven flow that connects all digital models and information across the product's lifecycle [5] offers a solution to the first challenge. Concurrently, advancements in LCA software and databases address the second. This paper argues that the *integration* of these two digital pillars is the key to unlocking truly effective and optimized Sustainable Product Design for Disassembly [9].

1. Literature Review

1.1 Design for Disassembly (DfD): Early work by Boothroyd & Dewhurst and subsequent ISO standards (e.g., ISO 8887) established principles for DfD, emphasizing accessibility, standardized fasteners, and minimal material variety. Recent research focuses on quantitative metrics like Disassembly Time, Degree of Disassembly, and indices for recyclability [2, 7].

1.2 Digital Thread in Manufacturing: The Digital Thread is an evolving concept from Industry 4.0, creating an authoritative data backbone from concept to disposal [5]. It integrates IoT sensor data, CAD models, manufacturing process plans, and supply chain information. Its application for sustainability, however, remains underexplored [10, 14].

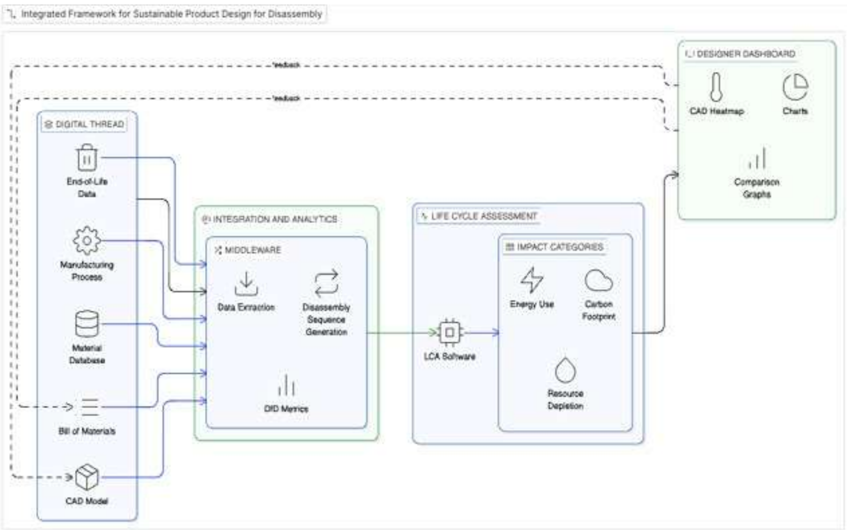
1.3 Lifecycle Assessment (LCA): LCA is the standardized (ISO 14040/44) methodology for assessing environmental impacts across a product's life [15]. The integration of LCA into design processes, known as Eco-design or Design for Environment (DfE), is well-established but often decoupled from real-time, granular product data [4, 6].

1.4 Research Gap: While prior studies advocate for DfD and use LCA to assess its benefits [2, 7], a significant gap exists in developing a *dynamic, data-driven framework* where DfD decisions are informed by live LCA fed directly from the Digital Thread [9]. This research aims to fill that gap

2. Proposed Integrated Framework

The proposed framework (Figure 1) creates a closed-loop feedback system between design, assessment, and optimization.

Figure 1: Integrated Digital Thread–LCA Framework for DfD



2.1 The Digital Thread Layer: This forms the data infrastructure. It links:

Design Data: 3D CAD models (with part geometry, metadata), Bill of Materials (BOM), joinery/connection data.

Material Data: Specific material IDs linked to databases containing environmental profiles (e.g., Ecoinvent, material passports).

Process Data: Assembly sequences, fastener types/torque, use of adhesives/contaminants.

End-of-Life (EoL) Data: Hypothesized or real disassembly sequences, sorting, and recycling process data.

2.2 The Integration & Analytics Layer: This is the core "brain" of the system. A middleware or PLM/PDM system with APIs extracts relevant data from the Digital Thread. It automatically:

Generates Disassembly Sequences: Using algorithms based on geometry and connection data.

Calculates DfD Metrics: Computes disassembly time (using MTM or similar standards), component purity, and separation effort [2].

Prepares LCA Inputs: Translates product data into inputs for LCA software (e.g., SimaPro, openLCA).

2.3 The Lifecycle Assessment (LCA) Layer: An LCA engine, called via API, performs impact assessments based on the dynamic inputs. It evaluates multiple impact categories (Global Warming Potential, Resource Depletion, etc.) for different EoL scenarios (reuse vs. recycle vs. landfill).

2.4 The Designer Decision Support Dashboard: A user interface presents actionable insights: Comparative environmental impact of different design variants.

A "Sustainability Hotspot" map overlaid on the 3D CAD model, highlighting hard-to-disassemble or high-impact connections

Trade-off curves (e.g., cost vs. carbon savings from a more disassembly-friendly but expensive fastener)

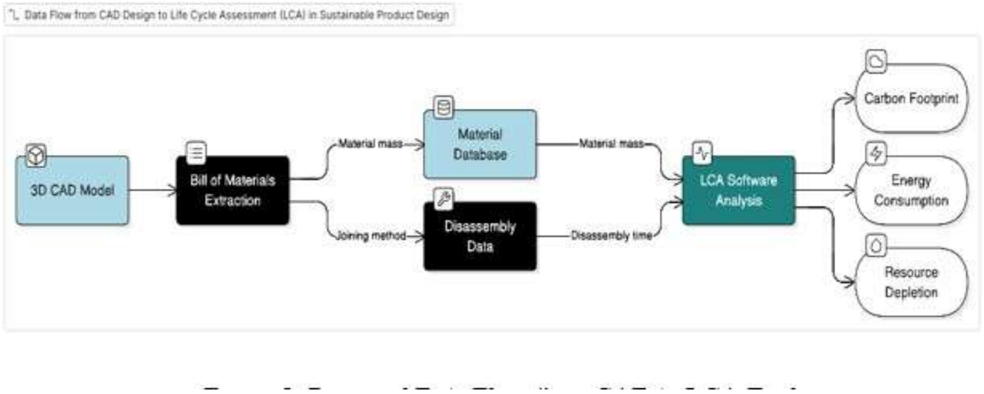


Figure 2: Proposed Data Flow from CAD to LCA Tool.

3. Conceptual Case Study: Electric Motor

To illustrate the framework, we consider the (re)design of a standard industrial electric motor, a complex assembly with metals, copper windings, magnets, and electronics [7, 16].

Product: 7.5 kW Three-Phase Induction Motor (Standard Industrial Type)

Baseline Design Components & Assembly Methods:

1. **Stator Core:** Stacked silicon steel laminations welded at 12 points around circumference
2. **Windings:** Copper wire (Class F insulation) impregnated with thermosetting varnish
3. **Rotor:** Aluminum die-cast squirrel cage bonded to steel shaft with interference fit
4. **Magnets (for efficiency enhancement):** NdFeB rare-earth magnets bonded to rotor using 2-part epoxy adhesive (15g per magnet)
5. **Housing:** Aluminum end caps secured with mixed M4 (8 pieces) and M5 (4 pieces) stainless steel bolts
6. **Bearings:** Two sealed deep-groove ball bearings (press-fit)
7. **Terminal Box:** Potting compound (polyurethane) encapsulating connections
8. **Cooling Fan:** Plastic fan riveted to shaft end

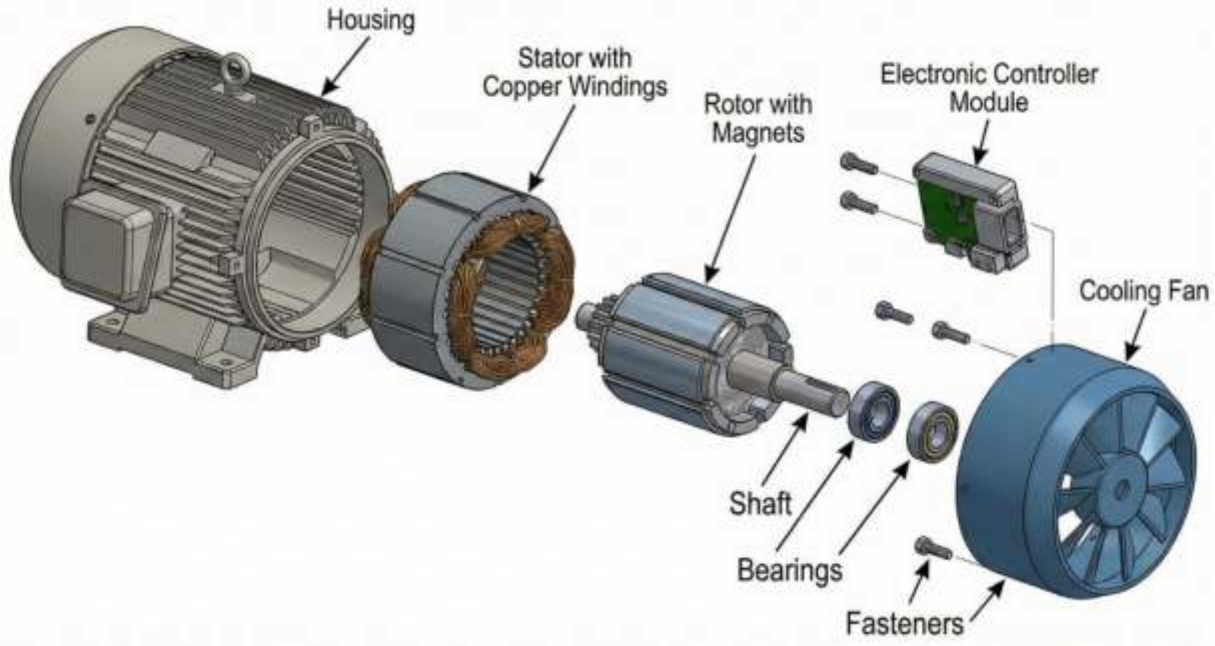


Figure 3: Electric Motor Case Study-Exploded View

Digital Thread Data Structure (Baseline):

Sr. No.	Component	Material	Mass (kg)	Connection Method	Disassembly Classification
1.	Stator Core	M400-50A Steel	12.4	Welding (12 spots)	Destructive
2.	Windings	Copper + Insulation	3.2	Varnish impregnation	Destructive
3.	Rotor	AlSi9Cu3 + Steel	8.7	Interference fit	Semi-Destructive
4.	Magnets	NdFeB (N48)	0.6	Epoxy adhesive	Destructive
5.	Housing	Al 6061-T6	5.8	Mixed M4/M5 bolts	Reversible
6.	Bearings	Steel + Rubber	0.4	Press fit	Semi-Destructive
7.	Terminal Box	PU Potting	0.3	Encapsulation	Destructive
8.	Cooling Fan	ABS Plastic	0.2	Rivets	Destructive

Table 1. Digital Thread Data Structure

Baseline Disassembly Analysis (Automated by System):

Disassembly Sequence Score: 28/100 (Poor)

Estimated Complete Disassembly Time: 47 minutes (using MTM-1 analysis) **Theoretical Material Recovery Rate:** 68% (32% material loss in shredding/processing) **Critical Barriers:** Epoxy bonding (magnets), welding (stator), potting (electronics)

Baseline Design: Uses permanent adhesive for magnet bonding, mixed M4/M5 stainless steel bolts, and potting compound for electronics.

Digital Thread Data: CAD model annotates all connections. BOM lists material of each part (NdFeB magnets, Cu wire, steel laminations). Process plan specifies adhesive type and quantity.

Scenario Analysis using the Framework:

1. **Scenario A (Baseline):** The system simulates destructive disassembly, calculates high energy use for shredding/separating, and the LCA module shows significant resource loss and high carbon footprint from virgin material replacement.
2. **Scenario B (DfD Optimized):** Designer modifies the model: replaces adhesive with a mechanical clamp for magnets, standardizes all fasteners to M5, and uses a modular, socketed electronic controller. The Digital Thread updates instantly.

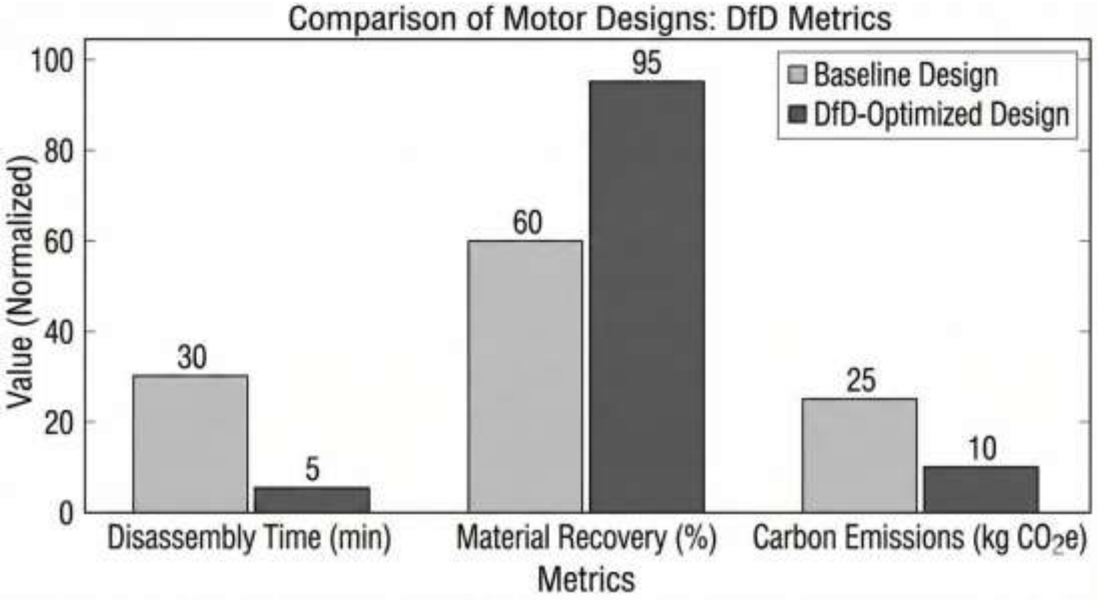


Figure 4: Baseline vs DfD-Optimized Motor Design

1. **Real-Time Feedback:** The analytics layer calculates a **40% reduction in estimated disassembly time**. The LCA module, using updated material recovery rates, shows a **15-20% reduction in Global Warming Potential** for the recycling scenario due to higher purity of recovered copper and steel, and the potential for magnet reuse.

   Dashboard Output: The designer sees a side-by-side comparison of both scenarios, with the CAD model highlighting the clamped magnet (now green/high-value) versus the adhesively bonded one (previously red/waste).

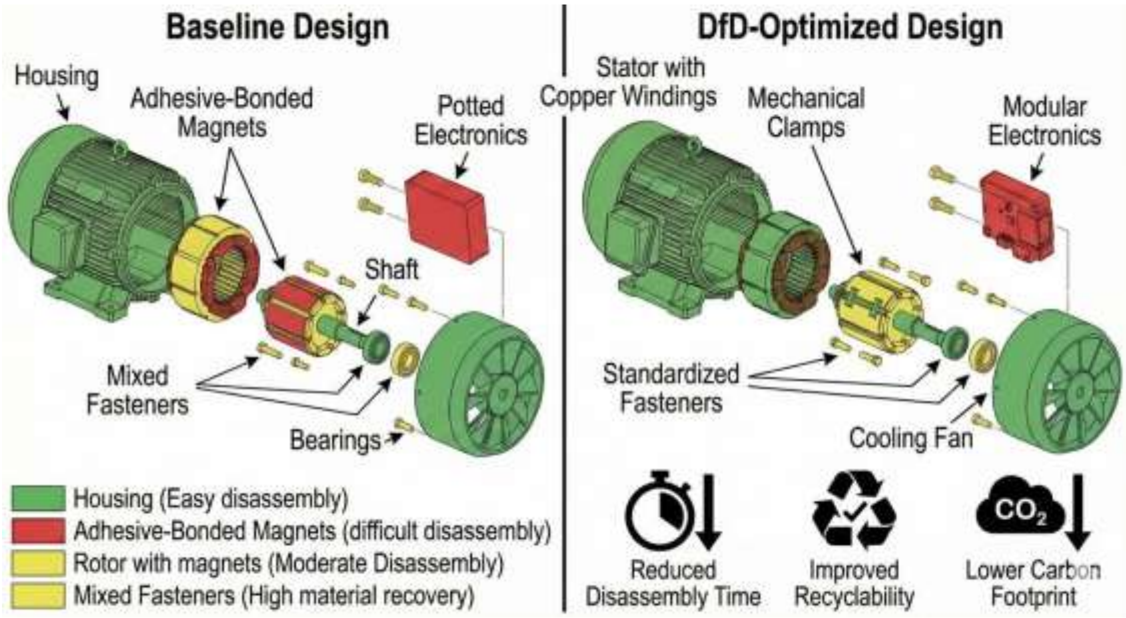


Figure 5. Baseline Vs DfD-Optimized Electric Motor Design

2. Discussion

This integrated framework directly contributes to the conference's exploration of digital transformation for sustainability:

From Qualitative to Quantitative: It moves DfD from a checklist to a data-driven optimization problem.

Proactive Sustainability: It embeds LCA at the "moment of decision" in CAD software, enabling true eco-design.

Management Implications (Aligns with *Sustainable Management Practices*): The framework provides managers with quantifiable sustainability metrics (kg CO2e saved, % material value recovered) to justify DfD investments and report on ESG (Environmental, Social, and Governance) goals.

Policy & Standards (Aligns with *Sustainability & Policy Frameworks*): Such a system can facilitate compliance with emerging policies like Extended Producer Responsibility (EPR) and Digital Product Passports (DPP) by generating verified, data- rich end-of-life profiles.

Challenges: Implementation hurdles include the cost of integrating legacy systems, the need for comprehensive material databases, and training designers in this new workflow.

3. Conclusion and Future Work

This paper presents a conceptual framework for revolutionizing Sustainable Product Design for Disassembly by integrating the Digital Thread with Lifecycle Assessment tools. By creating a seamless flow of information from design to end-of-life and enabling real-time environmental impact feedback, the framework empowers mechanical engineers and designers to make informed decisions that significantly enhance circularity.

Future Research will focus on:

1. Developing a practical software plugin to prototype this integration between a common CAD platform (e.g., SolidWorks, Fusion 360) and an open-source LCA tool.
2. Creating a standardized data schema for "disassembly information" to be carried within the Digital Thread.
3. Exploring the role of AI in automatically generating and ranking optimal disassembly sequences based on combined economic and environmental criteria.

The convergence of digital and sustainable transformations is not merely an opportunity but a necessity. This research outlines a tangible pathway for the mechanical engineering community to lead in building a circular, resource-efficient future.

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