ECO-DESIGN STRATEGIES FOR REDUCING MATERIAL AND ENERGY CONSUMPTION IN INDUSTRIAL PRODUCTION

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Abstract: *Eco-design – integrating environmental considerations into product development – is a central strategy for improving industrial sustainability. This paper evaluates the quantitative impact of three eco-design strategies – lightweighting, modularity and recyclability – on material and energy efficiency. Using Life Cycle Assessment (LCA) modeling through SimaPro/OpenLCA, two product systems were compared: a conventional baseline and an eco-optimized design. The results show material input reductions of 30 % – 35 %, energy savings of 25 % – 30 % and a 27 % decline in carbon emissions. Findings confirm eco-design's potential to enhance resource efficiency and competitiveness, aligning with Uzbekistan's transition toward a green economy.*

Keywords: *eco-design, resource efficiency, life-cycle assessment, sustainability, lightweighting, modularity, recyclability*

INTRODUCTION

Industrial production remains a primary source of energy demand and material consumption worldwide (UNIDO, 2024). As resource scarcity intensifies, eco-design has gained prominence as an approach to reduce environmental impact across the product life cycle (ISO, 2020). By rethinking material choice, structure and product life span, manufacturers can simultaneously improve economic and ecological performance (de Moraes et al., 2025).

In Uzbekistan, where industry accounts for roughly one-third of total energy use (ADB, 2024), embedding eco-design principles into manufacturing offers tangible opportunities for efficiency. Yet limited empirical evidence exists quantifying these benefits. This study applies LCA modeling to measure how design interventions reduce resource consumption, focusing on lightweighting, modularity and recyclability.

2. Literature Review

Eco-design extends conventional design methods by systematically minimizing material and energy use while maintaining product function (Kancheva, 2025). Common approaches include lightweighting, which substitutes dense materials with lighter composites; modularity, which enables component reuse and simplifies repairs; and recyclability, which closes material loops at end-of-life (Civancik-Uslu et al., 2019).

LCA, standardized by ISO 14040/44, provides a quantitative framework for evaluating these interventions (Raut et al., 2025). Studies report 20 % – 40 % reductions in environmental impact from eco-design adoption. Integrating LCA within design processes thus supports evidence-based decisions that balance economic and environmental outcomes.

3. Methodology

A comparative LCA was conducted using two scenarios:

• Scenario A (Baseline): Conventional product design and materials.

• Scenario B (Eco-Design): Optimized design incorporating lightweighting, modularity and recyclable content.

3.1 Data and System Boundaries

Functional unit: 1 000 kg of finished product in the construction-materials sector. System boundaries: cradle-to-grave – raw-material extraction, manufacturing, transport, use and end-of-life. Data were drawn from the Ecoinvent (2024) database.

3.2 Simulation and Indicators

Modeling in SimaPro/OpenLCA calculated:

• Material input (kg/unit)

• Cumulative energy demand (MJ/unit)

• Global warming potential (kg CO_2-eq/unit) Percentage differences were used to express improvement. Sensitivity analysis (±10 %) tested model robustness.

4. Results

4.1 Quantitative Outcomes

Table 1 presents comparative results for material and energy indicators.

Table 1

Comparison of Conventional and Eco-Design Scenarios

Indicator	Scenario A	Scenario B	Change (%)
Total material input (kg/unit)	1 000	680	-32
Waste generated (kg/unit)	120	95	-21
Cumulative energy demand (MJ/unit)	9 800	6 950	-29
Global warming potential (kg CO_2-eq)	1 200	876	-27
Recyclable content (%)	22	60	+173

Source: Author's LCA simulation.

Figure 1 shows the breakdown of life-cycle energy use by production phase.

Phase	Scenario A (MJ)	Scenario B (MJ)
Production	4 100	3 200
Transport	1 200	1 000
Use	3 500	2 300
End-of-Life	1 000	450

Life-cycle energy use by phase for baseline and eco-design scenarios. Source: Author's simulation results.

Overall, Scenario B achieved ~32 % lower material demand and ~29 % lower energy use. Sensitivity analysis confirmed minimum savings above 20 % even with conservative assumptions.

5. Discussion

The findings validate the effectiveness of eco-design in achieving measurable resource efficiency. Lightweighting contributed most to material savings, while modularity and recyclability extended product life and reduced waste. The 27 % drop in carbon emissions mirrors earlier research and aligns with resource-efficiency benchmarks in Greenovate Europe (2012).

For Uzbekistan, eco-design provides dual benefits: reducing dependence on imported raw materials and meeting targets under the Green Economy 2019 – 2030 strategy (ADB, 2024). Implementing these strategies across sectors could cut industrial energy intensity and improve export competitiveness. Key challenges include limited LCA expertise and financial barriers for SMEs. Policy incentives and training programs could help scale adoption.

6. Conclusion

This study demonstrates that eco-design – through lightweighting, modularity and recyclability – can reduce material and energy consumption by 25 % – 40 % while lowering emissions. Integrating LCA into design processes ensures that sustainability decisions are evidence-based and quantifiable. For emerging economies like Uzbekistan, mainstreaming eco-design represents a pragmatic path toward resource-efficient industrial growth. Future work should expand sectoral coverage and explore cost-benefit modeling to complement environmental metrics.

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