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Eco-Design as a Catalyst for Circular Innovation: A Knowledge-Based Framework to Sustainable Product Development.

E Monticelli & F Zurlo, Politecnico di Milano, Italy

The material consumption, energy use, and end-of-life disposal of Small Domestic Appliances (SDA) pose significant environmental challenges. Their high turnover rate, short lifespan and low recyclability compactness contribute to resource depletion, high greenhouse gas emissions and the growing issue of electronic waste. In addition, the rising consumer demand for sustainability, coupled with stringent regulations, such as the EU Eco-design Directive and the Circular Economy Action Plan, is accelerating the shift by manufacturers from traditional linear models to circular innovation. Central to this transition is the adoption of design approaches that enable practitioners to integrate sustainability principles early in the product development process while also building new competencies in developing solutions that reduce environmental impacts at every stage of the product life cycle. The paper presents the case study of a major SDA manufacturer that has adopted a knowledge-based framework to integrate Eco-design strategies into its product development process. To achieve this, the company commissioned the LeNSlab (Design and System Innovation for Sustainability) at the Department of Design, Politecnico di Milano, to develop, in collaboration with an internal team of experts, a company-specific *Handbook of Guidelines to Design Low-Environmental Impact Products*. The handbook provides actionable tools for SDA product developers, including seven Eco-design strategies, 27 sub-strategies, and 157 detailed guidelines and checklists. These tools address three core areas of circular innovation: resource consumption, circular design principles, and sustainable materials.

To test the handbook's practical effectiveness, ten pilot projects were selected to cover the different product ranges within the company's portfolio, ensuring the inclusion of their specificities. This approach allowed for a comprehensive evaluation across various product categories. Workshops were organized, involving a large portion of the product development community, including engineering, design, and marketing teams. During these workshops, participants meticulously applied the full handbook's checklists to identify actionable Eco-design opportunities in the early stage of the pilot project comparing each of them to the design specifications of a previous-generation model. The checklists provided a qualitative method for a systematic assessment while promoting cross-functional discussion around the implementation of the seven Eco-design strategies uncovering organizational challenges and opportunities in their execution.

By using sustainable design tools, such as the Eco-design Strategy Wheels, to analyze the outcomes of each pilot project and by evaluating the specific type of concepts generated during the workshops, it was possible to understand how effectively the checklists guided the product development community toward the identification of circular innovation opportunities. The results highlighted the handbook's potential to facilitate the transition to a circular economy by enabling informed decision-making and fostering the adoption of a new Eco-design paradigm within the organization, although some limitations were also identified.

In conclusion, this research contributes to the discourse on circular innovation by presenting a replicable approach for aligning business practices with circular economy principles. The study also provides insights

into the mechanisms supporting this shift and outlines potential future research directions, including the refinement of Eco-design tools, enhanced integration of sustainability throughout product development, and strategies to scale circular innovation practices across organizations.