ABSTRACT

Decoupled Individual Producer Responsibility: Decision Models for Economically Viable Tire Circularity

PhD Thesis

by

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This thesis focuses on the challenges that limit the practical implementation of Individual Producer Responsibility (IPR) for End-of-Life Tires (ELTs) in India within the broader context of Extended Producer Responsibility (EPR). IPR shifts the responsibility of ELT management from the customers and municipalities to the tire producers and encourages design improvements for tire circularity. Although Collective Producer Responsibility (CPR) remains the most popular practice, its fee-based structure creates limited motivation for Design-for-Recyclability (DfR). In contrast, IPR links the recycling costs to the design of the tire and supports innovation. Rapid expansion of the Indian tire industry creates an urgent need for a feasible, scalable, and regulatory-aligned solution for IPR adoption. Multiple barriers continue to restrict IPR implementation. For instance, high investment needs, limited infrastructure, and the absence of strategic guidance create significant constraints for the small and medium tire producers. This thesis aims to address these constraints by developing an economically viable, practical, holistic, and regulatory-aligned Circular Supply Chain (CSC) framework. The framework integrates the upstream design responsibility with the downstream end-of-pipe waste management responsibility to support a circular and innovation-driven tire ecosystem.

The literature reveals five major research gaps. First, the producers face a strategic dilemma between establishing an in-house recycling facility and collaborating with the third-party recyclers. The literature provides limited quantitative guidance for this decision, especially under the real-world budget and capital constraints. Second, the literature lacks a well-defined, adaptable, and practical regulatory-aligned framework for collaboration that reflects the Indian EPR legislation while incorporating the global best practices. Third, systematic methods for designing fair and viable collaboration contracts under uncertainty remain underexplored, even though appropriate financial incentives for all the stakeholders are essential for successful partnerships. Fourth, the upstream pre-market producer responsibilities receive limited attention in majority of the studies in EPR, even though true circularity begins much earlier in the supply chain through sustainable raw material sourcing. Finally, there is a lack of research on comprehensive CSC network optimization models that explicitly consider the EPR

legislation and the financial interests of multiple stakeholders under uncertainty. To address these gaps, this thesis develops four research objectives, as discussed below.

The first objective introduces a two-stage stochastic mixed-integer nonlinear programming model to evaluate the trade-off between the in-house recycling and collaboration with the third parties under budget and capital constraints. This stochastic decision model helps the producers select the optimal IPR strategy. The objective uses the McCormick relaxation-based linearization techniques and Sample Average Approximation (SAA) to solve the model, along with three metaheuristic algorithms for large instances. The second objective designs a regulatory-aligned collaborative circular supply chain (CCSC) network architecture that clarifies the structural constraints, stakeholder roles, and material flow logic for operationalizing IPR in the tire industry. The CCSC architecture is grounded in the Indian EPR legislation and the benchmark practices from the EU, Canada, and the United States. This objective promotes a cost-effective collaboration structure that repurposes tire dealers as take-back agents. The third objective develops a Z-number Slacks-Based Measure (ZN-SBM) Data Envelopment Analysis model, which is used to construct a decision support framework for sustainable raw material supplier selection with imprecise information. The framework evaluates the suppliers by considering the economic, social, and environmental criteria, including the critical Pre-Market Producer Responsibility (PPR) metrics such as hazardous substance control, conformance to the PPR standards, recycled content, and Design-for-Environment score. The fourth objective constructs a Z-number-based multi-period optimization model that quantifies the economic viability of the CCSC network under uncertainty. In addition, this objective also puts forward a Simple Additive Weighting-based Taguchi method to design the optimal collaboration contracts.

The results from the first objective indicate that collaboration with the third-party recyclers creates higher economic feasibility for the tire producers under the budget and capital constraints. In the second objective, a qualitative validation through legislation alignment, stakeholder analysis, SWOT analysis, TOWS matrix, and Sustainable Development Goals assessment confirms that the CCSC framework supports transparent operations, efficient collection, and structured collaboration. The decision support framework developed in the third objective identifies the most sustainable raw material suppliers across seven distinct raw material types required for tire production, namely “synthetic rubber,” “natural rubber,” “carbon black,” “steel,” “textile,” “zinc oxide” and “sulfur.” It provides a reliable foundation for the upstream decision-making within the CCSC network. Finally, in the fourth objective, a numerical study shows that the proposed CCSC network can generate positive net present values for the producer, tire dealers, and recyclers. The results indicate that the producer achieves viable collaboration outcomes if they provide sufficient financial incentives to the partners. It increases participation and ensures compliance more effectively than paying the penalties for any unfulfilled EPR obligations.

Overall, the thesis contributes a structured, quantitative, and regulatory-aligned approach for implementing IPR in the Indian tire industry. The proposed CCSC framework integrates the upstream and the downstream producer responsibilities, supports sustainable material sourcing, designs feasible collaborative networks, and identifies the economically viable conditions for circular operations. The combined insights highlight that IPR implementation can be practical and profitable when supported by collaborative supply chain design, advanced decision models, and incentive-aligned contracts.

Keywords: End-of-Life Tires (ELTs), Collaborative Circular Supply Chain (CCSC), Individual Producer Responsibility (IPR), Extended Producer Responsibility (EPR), Design-for-Recyclability (DfR), Sample Average Approximation (SAA), Z-number Slacks-Based Measure (ZN-SBM), Z-number-based multi-period optimization model, Taguchi method.