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Conceptual Framework for Enabling Cross-Industry Circular Material Flows in the Tire Industry

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Abstract: Circular economy (CE) strategies have become central to sustainable transformation in resource-intensive industries, yet their implementation remains challenging due to fragmented approaches and limited systemic integration. While the tire industry generates over one billion end-of-life tires annually and faces mounting environmental pressures, existing CE frameworks predominantly focus on single-industry perspectives and lack integration across material innovation, product development, and system-level dynamics. To address this gap, this paper proposes a conceptual framework integrating material science, product innovation, and System Dynamics modeling to facilitate cross-industry circular material flows in the tire sector. The framework focuses on two innovation pathways: Waste-to-Tires (utilizing renewable or waste-derived inputs) and Used-Tires-to-Products (repurposing end-of-life tires across industries). Operating across three analytical levels: material, product, and industry, the framework enables iterative development, stakeholder engagement, and systemic policy evaluation. The approach aims to enhance CE readiness, support multi-industry collaboration, and provide actionable insights for policymakers and practitioners seeking sustainable industrial transformation.

Keywords: circular economy; cross-industry innovation; system dynamics; tire recycling; repurposing

1 INTRODUCTION

Circular economy strategies have become increasingly central to the sustainable transformation of resource intensive industries [1]. The concept of circular economy (CE), popularized by the Ellen MacArthur Foundation in 2005, presents a paradigm shift from the traditional linear "take make dispose" model to a closed loop and regenerative system [2]. CE prioritizes the application of R strategies such as recycling, repurposing, reusing, refurbishing, remanufacturing, reducing waste and minimizing resource and energy consumption [3]. The European Commission further promotes CE as a pathway to sustainable economic growth, innovation, and job creation [4].

In the case of the tire industry, each year, more than one billion end-of-life tires (ELTs) are discarded worldwide. A large share of these is either landfilled or incinerated, posing serious environmental and public health risks [5]. Within the European Union, instruments such as the Waste Framework Directive and the European Green Deal provide a regulatory foundation for circularity [6-[7]. However, progress remains uneven. A significant proportion of ELTs in Europe are still incinerated, while markets for recovered materials are not yet fully developed [7]. High processing costs, unclear end of waste definitions, and insufficient demand side policies continue to hinder effective implementation [8]. In regions with underdeveloped recycling systems, such as parts of Southeast Europe, recovery rates often fall below 60% [9]. While the need for systemic change is widely recognized, practical and scalable solutions are still lacking. Recent calls from the European Tyre Recycling Association highlight the urgent need for harmonized standards, collaborative research and development, and incentive structures to support innovation [10].

These European challenges reflect a wider global reality. Growing volumes of ELTs, continued reliance on non-renewable material inputs such as carbon black, limited market acceptance for refurbished tires, and restricted possibilities to recycle or repurpose ELT materials have placed the tire industry worldwide under mounting pressure to innovate [11].

Besides within-industry tire recycling and refurbishing activities, promising CE innovation approaches for the tire industry are related to cross-industry material streams [12]. The first approach, on the input side of the tire industry, relates to using new, renewable or waste materials from other industries in tire production [13], and the second approach, on the output side of the tire industry, relates to recycling or repurposing ELTs into new products in other industries [14].

Regarding the first cross-industry innovation approach, focusing on material input streams and how they could change the value creation system of the tire industry towards a more sustainable one, tires are composed of a complex mix of materials, including natural and synthetic rubber, steel, textile reinforcements, and various chemical additives [15]. Among these, fillers such as carbon black and silica play a crucial role in enhancing tire performance, durability, and cost-efficiency. Fillers are particularly interesting to focus on because they account for a significant portion of the tire's mass and environmental footprint [16], and their substitution or modification can open pathways for integrating secondary raw materials or renewable sources into tire production. Although technological alternatives such as bio-based fillers and recovered carbon black show promise, they remain limited by economic volatility, uncertain demand, and inconsistent regulatory conditions [17].

Regarding the second innovation approach, focusing on the cross-industry use of ELTs, besides the above-mentioned shortcomings of systematically collecting ELTs at all, there is to date only a limited number of products or rather product categories resulting from their recycling or repurposing [14]. Common applications include low value products such as playground surfaces, rubber mats, construction infill, or fuel in cement kilns [18]. These uses often fail to capture the full material potential of ELTs due to several challenges. A major issue lies in the heterogeneous and degraded nature of the material, which often contains a complex mix of components already mentioned above [19]. The presence of contaminants and the undefined composition make it difficult to ensure material purity, consistency, and safety, especially for applications requiring high performance or strict regulatory compliance. In some cases, concerns about toxicity or the long-term environmental impact of additives further hinder product innovation [20]. Opening up the material stream of ELTs towards new products and the related business models could not only spur innovation activities in other industries but also increase the demand for systematic collection of ELTs [21].

This paper integrates both the input and the output materials perspectives described above and supports the tire industry's future cross-industry innovation approaches through the development of a three-level system framework. This framework integrates materials science, product innovation, and qualitative as well as quantitative System Dynamics modeling to explore and enable new pathways and business models for resource recovery and reuse. In more detail, the framework combines both innovation approaches described above. The first, Waste-to-Tires, focuses on identifying and evaluating alternative waste streams as inputs for tire manufacturing and how this affects existing value creation structures. The second, Used-Tires-to-Products, explores new applications and related business models for recycled tire materials across various product markets. Together, they are embedded within a three-level structure - material, product, and industry or company - allowing for iterative development, stakeholder engagement, scenario-based modeling, and a comprehensive system view.

By combining laboratory material testing, product prototyping, business model design, and both qualitative and quantitative System Dynamics analysis, the framework helps to generate early-stage insights and tools that support sustainable innovation and long-term transformation. Research following this framework can offer practical guidance for policymakers, researchers, and industry stakeholders working toward more circular systems.

The paper is organized as follows: Section 2 outlines recent literature in CE, material development in tire production, ELT innovations, and System Dynamics-based methods for assessing business models. Section 3 presents the methodology used to derive the framework, which is discussed in Section 4. Section 5 concludes the paper and outlines future research directions.

2 RESEARCH CONTEXT

2.1 Circular Economy: Principles and Implementation in Manufacturing

Transitioning to CE requires systemic changes in business models (BMs), organizational structures, and value creation mechanisms [22]. At the operational level, this includes redesigning products for longevity and recyclability, among other changes [23].

The manufacturing sector has so far addressed CE principles mainly by incorporating cleaner production, reuse, remanufacturing, and servitization strategies [24]. However, many companies face skill and resource gaps, hindering implementation [25]. Recent research highlights that the integration of CE with Industry 4.0 (I4.0) technologies introduces additional complexities and skill requirements [26]. This 'twin transition' requires integrated business strategies that leverage both digital capabilities and circular economy models to create value across industries [27]. The convergence of digital technologies with circular practices demands not only technical competencies but also organizational capabilities to manage data-driven processes and cross-functional collaboration [28]. Studies emphasize that addressing skill gaps in both CE and I4.0 domains requires comprehensive training programs, knowledge transfer mechanisms, and workforce development strategies [29-[31]. These challenges are particularly pronounced in resource-intensive industries where digital transformation must occur alongside material and process innovations. Pigosso and McAloone [23] identify eight key dimensions necessary for CE integration in manufacturing, ranging from organizational culture to regulatory frameworks. Chiappetta Jabbour et al. [22] emphasize that supportive policies and financial incentives are essential to foster such transformations. In low- and middle-income countries, limited awareness underscores the need for targeted education, innovation policies, and outreach to build CE capacity.

2.2 Circular Economy Frameworks

CE frameworks provide structured approaches for moving away from traditional linear models of production and consumption, emphasizing the continuous use of materials and the reduction of waste. Among the most influential is the Ellen MacArthur Foundation framework, which defines circularity through three core principles: eliminating waste and pollution, keeping products and materials in use, and regenerating natural systems [33]. Building on this foundation, the ReSOLVE framework offers six strategic action areas: regenerate, share, optimize, loop, virtualize, and exchange. These serve as practical guidelines for governments and businesses developing circular strategies [34]. Another widely adopted approach is the R-ladder framework, which is composed of several actions ranging from refuse, reduce, and reuse to recycle and recover [35]. This hierarchy helps prioritize interventions based on their potential environmental and economic benefits.

The United Nations developed the UNEP circularity approach [36], which is illustrated in Fig. 1. This figure details the shift from the traditional linear economy toward a closed loop system that retains material value across the product life cycle. This framework is based on the R-ladder with 9 steps, and at its core is the principle of reduce by design, which aims to minimize environmental impact from the outset [35]. The model contrasts the linear flow from extraction to disposal, with circular loops that not only reintegrate materials but also decrease resource extraction through rethinking, refusing, reusing, repairing, refurbishing, remanufacturing, repurposing, and recycling. These loops are categorized by interaction type: user to user (U2U), user to business (U2B), and business to business (B2B). By mapping these interconnected processes, the framework emphasizes the role of design, collaboration, and systemic thinking in enabling CE transitions. Practical examples of cross-industry material valorization, such as the utilization of construction and demolition waste as aggregates in new concrete production, demonstrate the technical feasibility and economic benefits of transforming waste into valuable secondary raw materials [37]. Such approaches provide templates for similar transformations in the tire industry.

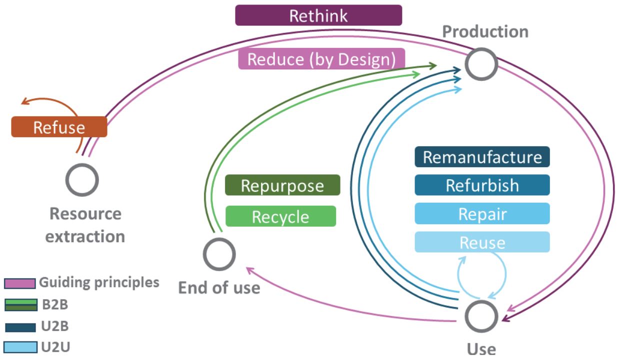


Figure 1 UNEP circularity approach adapted from [36]

There are also examples of frameworks developed for specific regions and contexts. For instance, Demko-Rihter et al. [38] proposed a framework tailored for firms in developing countries (using a Serbian company as a case study) to assess their CE readiness. The authors focused on both product and business model perspectives and provided practical guidance through maturity assessment, KPI definition, and planning for circularity improvements. Despite these contributions, there is still a clear gap in models that address cross-industry interactions and material flows. Most existing frameworks focus on individual industries, limiting their ability to capture interdependencies and optimize resource use across multiple industries. Developing integrative frameworks that consider cross-industry value chains and promote coordinated actions is essential for advancing more effective and resilient CE transitions.

2.3 Challenges to Circular Economy in the Tire Industry

The transition to a CE in the tire industry is limited by persistent environmental, technological, economic, and regulatory challenges. Tire manufacturing depends heavily on non-renewable materials, particularly carbon black (CB), whose production involves high energy consumption and leads to substantial greenhouse gas emissions and environmental degradation [5]. Each year, more than one billion ELTs are generated globally, yet only 35 to 60% are recovered through recycling or repurpose. The rest are commonly incinerated or disposed of in landfills, which results in significant environmental and public health concerns [9]. Landfilled tires contribute to soil and groundwater contamination through leachate release, while open storage or uncontrolled burning can produce harmful air pollutants and create breeding grounds for disease carrying insects such as mosquitoes.

Various recycling methods are used to recover value from tire waste, but each presents environmental trade-offs [11]. Pyrolysis, a thermal decomposition process, produces outputs such as oil, gas, and recovered CB, and generates lower carbon dioxide emissions compared to incineration, around 54.5 kilograms per ton of tire waste versus 220 kilograms per ton [39]. However, pyrolysis still emits volatile organic compounds, heavy metals, and fine particulates, which pose risks if emission controls are inadequate [32]. Devulcanization allows rubber to be reused in new compounds and applications, potentially replacing up to 65% of raw rubber.

Mechanical recycling, such as grinding tires into crumb rubber for use in asphalt or cement composites, offers additional carbon savings (up to 1.6 tons of carbon dioxide equivalent per ton of tire waste) and a 24% reduction in emissions when used in cement [33]. However, this pathway is limited by product inconsistency, microplastic generation, and weak market demand. Other emerging applications, such as the use of tire derived porous carbon for water purification or activated carbon for pollutant adsorption, show promise but remain underdeveloped and are not yet widely adopted [34].

Regulatory frameworks also pose challenges to CE adoption. While the European Union Waste Framework Directive and the European Green Deal promote repurposing and recycling, implementation is slowed by inconsistent definitions of waste recovery, uneven enforcement, and insufficient policy harmonization across member states [7, 8]. Market barriers include low demand for recycled tire materials, high processing costs, and the lack of common technical standards. Initiatives, such as the coordination efforts led by the European Tyre Recycling Association [10], aim to address these barriers by promoting research, investment, and shared standards.

Beyond these traditional barriers, the tire industry's transition to CE is increasingly shaped by the convergence with digital technologies and Industry 4.0 capabilities [26]. Recent sector-specific research on CE implementation in the tire industry identifies that successful transitions require coordinated efforts across the entire value chain, including enhanced data sharing mechanisms, stakeholder collaboration platforms, and the development of harmonized standards for recycled materials [32]. Applications of digital twins in the tire industry demonstrate how digital technologies can support environmental performance evaluation and circular practices [29]. While digital technologies offer opportunities for improved material traceability, process optimization, and supply chain transparency [29], realizing these benefits demands substantial investments in digital infrastructure, workforce capabilities, and organizational change management [30,[31]. These insights underscore that effective CE frameworks must integrate both technological innovation and systemic organizational and policy changes to overcome the multifaceted barriers facing the tire industry.

2.4 New Materials and Bio-Based Alternatives in Tire Production

In the effort to develop more sustainable rubber products, researchers have increasingly investigated the use of bio-based fillers as partial substitutes for CB, a petroleum-derived material widely used as a reinforcing agent in rubber compounds [17]. Conventional CB production involves high-temperature oxidation (1400-2000 °C), resulting in high energy consumption and significant greenhouse gas emissions [43]. Additionally, the manufacturing and processing of CB are associated with the release of particulate matter and volatile organic compounds, which pose respiratory and cardiovascular health risks to workers and surrounding communities [20].

The substitution of CB with bio-based alternatives addresses both environmental and health-related concerns. The structural properties of CB are key to its reinforcing function in rubber products [13], and these characteristics can be partially replicated using lignin and other bio-derived materials. Lignin-based hybrid fillers, in particular, have shown potential to reduce viscoelastic energy losses and improve anti-aging resistance, flexibility, and processing efficiency in rubber formulations [44]. These improvements translate into longer product life cycles, which support CE objectives by delaying material disposal and reducing demand for virgin inputs.

Moreover, bio carbons derived from agricultural or industrial waste streams, especially those with low ash content, have demonstrated strong performance as CB replacements in styrene butadiene rubber. Partial substitutions of 25-50% biocarbon not only preserve mechanical integrity but, in some cases, improve tensile strength, elongation, and toughness [44]. For instance, herbal waste (specifically herbal dust ash from filter-tea production) has been shown to function effectively as an eco-friendly filler in natural rubber composites, helping to repurpose waste while maintaining material performance [45]. These findings indicate that bio-based fillers can reduce the environmental footprint of rubber manufacturing by lowering fossil fuel dependence, minimizing emissions, and valorizing biomass waste.

2.5 End-of-Life Tires as a Resource: Technological Advances and Emerging Applications

As mentioned in section 2.3, ELTs pose a significant environmental challenge due to their large volume, resistance to degradation, and pollution potential [5]. However, advancements in recycling and repurposing technologies have increasingly turned ELTs into valuable secondary materials [14]. Tab. 1 summarizes potential uses of ELTs. Current management strategies focus on material recovery, particularly through crumb rubber, which is widely used in asphalt, sports surfaces, playgrounds, and construction due to its durability, elasticity, and shock absorption [41].

Pyrolysis is a promising thermochemical method that converts ELTs into oil, CB, and gas. These outputs are used in energy production, industrial processes, and as additives in manufacturing [40]. Civil engineering has also adopted ELT materials in applications such as lightweight fill, drainage layers, and erosion control, highlighting their functional benefits in geotechnical uses [17].

Recent innovations have broadened ELT applications. Devulcanization and micronized rubber powders allow for reintegration into new rubber products, including automotive parts, industrial seals, and footwear [17, [46]. Tire derived aggregates are under investigation for use in concrete and road base layers, offering improved insulation and drainage. ELTs are also used in molded rubber goods, artificial reefs, and energy recovery systems where other recycling options are limited [40].

Despite progress, several barriers remain. These include inefficient collection systems, limited pyrolysis performance, and weak market demand for some recycled products [47]. Policy instruments such as extended producer responsibility, landfill restrictions, and sustainable procurement are increasingly supporting circular practices and innovation in ELT processing [48]. Achieving large scale and economically feasible solutions will require collaboration among industry, government, and academia to advance technology and strengthen markets for recycled ELT products [49]. Lessons from analogous end-of-life product streams, such as end-of-life vehicles, demonstrate that successful recycling systems require comprehensive regulatory frameworks, established collection infrastructure, and coordinated stakeholder collaboration [50]. These cross-sectoral insights underscore that ELT management can benefit from adopting proven approaches from other automotive-related waste streams while addressing tire-specific material challenges.

Table 1 Summary of techniques and applications for ELTs' recycling and repurposing

Technique	Description	Main uses
Crumb Rubber Production	Grinding ELTs into small particles	Asphalt, sports surfaces, playgrounds, construction (shock-absorbing and elastic applications)
Pyrolysis	Thermochemical breakdown into oil, gas, and carbon black	Energy production, industrial processes, manufacturing additives
Devulcanization	Reverses vulcanization to make rubber reusable	New rubber products (e.g., automotive parts, industrial seals, footwear)
Micronized Rubber Powder (MRP)	Produces ultra-fine rubber particles	Integration into new rubber goods
Tire Derived Aggregates (TDA)	Shredded tires used as aggregate material	Road base layers, concrete, insulation, drainage
Molding	Forms recycled rubber into new shapes	Molded goods like mats, blocks, bumpers
Energy Recovery	Incineration or other methods to recover energy	Used when other recycling paths are not feasible
Civil Engineering Applications	Structural use of ELT material	Lightweight fill, drainage layers, erosion control, geotechnical applications
Artificial Reef Construction	Use of whole or processed tires in marine environments	Environmental applications like reef building

2.6 System Dynamics: A Modeling Approach to Support Strategy in Circular Economy

As a modeling and simulation approach, System Dynamics (SD) has become an established methodological approach for investigating the complex, nonlinear interactions characteristic [51] of sustainable transitions, particularly within CE and waste management systems [52, [53]. By explicitly modeling feedback loops, time delays, and interdependencies, SD enables the simulation of dynamic behaviors over time, offering valuable insights for both strategic planning and policy development.

The application of SD in the domain of solid waste management and CE strategy formulation has been extensively explored across diverse national contexts [53-[55]. These studies demonstrate the capacity of SD to capture systemic behavior under different intervention scenarios, assess long-term outcomes, and support the design of more resilient and adaptive waste systems.

In the context of tire and rubber recycling, SD has supported the holistic mapping of material flows and waste treatment processes, thereby enhancing long-term planning and improving resource efficiency [49]. It has also facilitated policy simulation by enabling stakeholders to test the impacts of regulatory changes, economic incentives, and behavioral shifts on system performance [53]. Furthermore, the integration of SD with complementary modeling techniques, such as Multi-Criteria Decision Analysis and Agent-Based Modeling, has enhanced its utility in complex decision-making environments, particularly in the evaluation of competing policy options [56].

Specifically, within the tire industry, SD models have been employed to identify inefficiencies such as excessive scrap generation and emissions of volatile organic compounds, while also evaluating downstream strategies for tire reuse and recycling [54]. As CE strategies become more complex and interdependent, SD offers a valuable lens for systemic decision making and transition planning.

2.7 System Dynamics for Supporting New Business Models

Innovating BM is critical in responding to technological change and sustainability demands [57]. SD can support business model innovation in two complementary ways: (1) through qualitative causal loop diagrams and system archetypes; and (2) through case-specific simulation. Qualitative modeling, such as causal loop diagrams (CLDs) and system archetypes

[58], supports early-stage exploration when data are limited. Following the standard modeling process [51], initial steps involve defining key variables and feedback structures. For example, qualitative models have been used to hypothesize rebound effects in the fashion industry, where improved production efficiency could unintentionally accelerate consumption [52]. Another study applied archetypal modeling to explore competitive advantage mechanisms in BMs based on new digital production technologies for individualized garments [60]. These qualitative models provide a foundation for later quantitative refinement and offer strategic insights for firms navigating uncertain innovation environments.

Simulation allows for dynamic analysis of complex systems, testing scenarios, and communicating results clearly [51]. It is particularly effective in modeling feedback loops, time delays, and nonlinearities in decision-making [61]. Applications range from project management [62] to analyzing apparel supply chains [63], and evaluating new BMs [59]. These capabilities underscore SD's relevance in guiding cross-industry CE strategies, particularly where innovation and uncertainty intersect.

3 METHODOLOGY

This study introduces an interdisciplinary conceptual framework to explore CE strategies with the tire industry at its center. Designed as both a flexible working model and a theoretical construct, the framework draws on SD while integrating insights from material science and business innovation. Its primary aim is to support a systemic transition toward circularity by addressing the complex interconnections across the tire value chain and cross-industry, from raw material sourcing to end-of-life recovery. Structured around three interrelated levels (material, product, and company or industry) the framework aligns each level with a distinct industry, establishing a cross-industry perspective on innovation, as illustrated in Fig. 2.

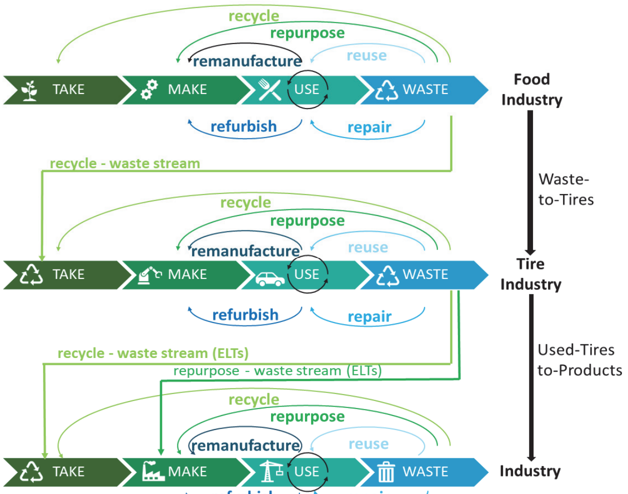


Figure 2 Cross-industry perspective of the conceptual framework

Rather than prescribing fixed solutions, the framework offers a flexible tool for analysis and design. It builds on earlier SD work in industrial ecology and waste management [54, [56], extending their scope to include material substitution dynamics and emerging BMs. By integrating theoretical insights with empirical modeling, the approach combines analytical depth with practical relevance.

A key methodological contribution is the iterative exchange of knowledge across industries. Technical constraints identified at the material level inform product design in adjacent industries, while system-level modeling insights feed back into business strategy and innovation planning. This cross-industry learning supports early detection of bottlenecks arising from interdependencies. The framework thus serves both as a diagnostic lens and a collaborative space for exploring scenarios and testing policies that span multiple industries, offering a realistic and scalable pathway for CE implementation.

SD is central to operationalizing the framework, with its ability to represent time delays, feedback effects, and actor interactions [64]. Qualitative modeling maps BM dynamics, while quantitative simulations assess systemic impacts over time, generating actionable insights for firms and policymakers.

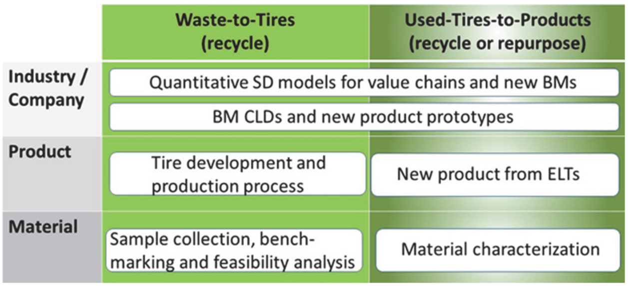
4 CONCEPTUAL CONTRIBUTION

The framework is built around the two cross-industry innovation approaches described in Section 1:

- Waste-to-Tires: Identifying and evaluating novel waste streams (e.g., recycled food packaging, tea bags, sawdust) as potential inputs into tire manufacturing, aiming to reduce reliance on raw materials such as CB [43].

- Used-Tires-to-Products: Recycling or repurposing ELTs into new product applications (such as rubber-based playground surfaces, industrial wheels, or architectural components) by exploring technical feasibility and market-fit of derived materials [17].

As illustrated in Fig. 3, the framework integrates material, product, and company/industry levels. At the material level, it supports the evaluation of alternative feedstocks for tire manufacturing, as well as secondary uses for recycled tire materials.



	Waste-to-Tires (recycle)	Used-Tires-to-Products (recycle or repurpose)
Industry / Company	Quantitative SD models for value chains and new BMs BM CLDs and new product prototypes	
Product	Tire development and production process	New product from ELTs
Material	Sample collection, bench-marking and feasibility analysis	Material characterization

Figure 3 Multi-level systems analysis framework

Laboratory analyses [43] follow standardized protocols, contributing to research infrastructure and future standardization. At the product level, insights from material testing are translated into the development and production processes on the Waste-to-Tires functional prototypes, supported by cost and viability assessments [65]. This stage serves as a bridge between material choices and broader system outcomes. The industry/company level incorporates both qualitative (CLDs) and quantitative (stock-and-flow modeling) tools from SD. Specific models must be built to test hypotheses and to be able to test policies and business scenarios [55]. The integration of SD adds a dynamic, feedback-oriented dimension to CE planning. Unlike static or linear approaches, SD captures complexities such as regulatory rebound effects, technology lock-ins, or behavioral delays [51], helping identify tipping points and unintended consequences.

Methodologically, the proposed framework demonstrates how early-stage data and prototype development can be iteratively embedded into system level simulations, offering a scalable approach to linking bottom-up innovation with top-down modeling, which is an essential capability for implementing CE in complex industrial sectors like tires. Through its three-level structure, the framework not only supports early phase circular design but also builds a practical knowledge base to inform decision making among businesses, researchers, and policymakers. Conceptually, it contributes to the emerging field of CE system design by explicitly integrating material innovation, product development, and systemic modeling within a two innovation streams, three-level architecture. In contrast to the often-isolated development of circular strategies, this framework emphasizes their interconnection, capturing real world feedback loops and interdependencies to enable more robust and actionable transitions.

5 CONCLUSION AND OUTLOOK

This paper introduces a novel conceptual framework for enabling CE transitions in the tire industry. Grounded in a three-level analysis and SD, captures the dynamic interconnections between material flows, product innovation, BMs, and policy mechanisms across cross-industry value chains. It distinguishes between two key innovation streams: Waste-to-Tires and Used-Tires-to-Products and situates them within a three-level structure covering the material, product, and industry/company dimensions. Each level corresponds to a distinct industrial domain, facilitating a cross-industrial perspective that uncovers early-stage opportunities, bottlenecks, and systemic risks. The rising volume of ELTs and limitations of current recycling systems underscore the urgency and relevance of such an integrated approach. Although still at a conceptual stage, the framework will be applied and tested in the Serbian tire industry.

The framework addresses policymakers, industry stakeholders, and researchers. Policymakers can use it to assess regulatory measures such as landfill bans or subsidies. Industry actors can explore renewable and waste-based inputs or ELT-derived markets. Researchers can connect material science insights with system-level modeling. Because stakeholders' decisions and investments can accelerate or block CE transitions, the framework will integrate actor roles, target audiences, and diverse datasets (i.e., LCA data, ELT collection forecasts, cost structures, and policy parameters) alongside qualitative inputs from stakeholders. This integration can strengthen its potential as a foundation for robust SD models that connect material-level innovation with industry and policy dynamics.

By bridging material science, product development, and system-level analysis, the framework offers a scalable tool for guiding circular innovation in the tire industry and related industries. Its core contribution lies in aligning bottom-up technological innovations with top-down system feedbacks and policy responses, thereby capturing interdependencies often overlooked in single-industry models. The planned application to the Serbian tire industry will provide a testbed for quantitative SD simulations, revealing how regulatory, technological, and market dynamics shape CE transitions. Ultimately, this multi-level, iterative modeling approach positions the framework not only as a research method but also as a practical decision-support tool. While the current application is industry-specific, the framework is designed to be adaptable to other industrial systems where CE transitions demand multi-stakeholder coordination and material innovation. By offering a bridge between circular product design, stakeholder behavior, and SD, this framework paves the way for more inclusive, anticipatory, and actionable CE strategies across industrial ecosystems.

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