PhD Thesis Proposal: Definition, development, and assessment of innovative indicators and optimization criteria to improve evaluation of regeneration value chains

Context

Recycling value chains in France and Europe face significant challenges due to the diversity of actors involved, the fragmentation of management systems, the heterogeneity of material flows, and increasing economic and regulatory constraints. This structural complexity is further amplified by the interdependence of processes, variability in available resources, and the growing need for industrial and technological sovereignty. While the literature on the circular economy is extensive, much of the existing research remains focused on local process optimization (e.g., energy efficiency, waste reduction, yield improvement) or on individual actors, without fully addressing the systemic dynamics and multi-scale interactions required to build robust and resilient recycling networks.

To address these challenges, recent studies emphasize the need to move beyond siloed approaches and develop systemic models capable of integrating the entire product life cycle, delayed decision feedback, sector-specific constraints, and multi-level governance mechanisms. These approaches must consider not only the physical and economic characteristics of materials but also the collaborative dynamics between heterogeneous actors, the uncertainty of material flows, market unpredictability, and the rapid evolution of technologies and regulations.

Problem Statement

This work proposes an innovative approach to structuring and managing recycling value chains as dynamic, interconnected, and territorially embedded networks. Based on Systems of Systems (SoS) engineering, the project aims to overcome the limitations of local optimization by integrating multi-level interactions, complex feedback loops, and sector-specific constraints. This vision facilitates the coordination of actors with potentially divergent goals, while providing the flexibility needed to respond to the uncertainties of material flows and the rapid changes in market and regulatory conditions. Digital sciences play a central role in this approach, providing the methods and tools needed to model, simulate, analyse, and orchestrate these complex networks while integrating technical, economic, environmental, and social constraints. The main research axes of the project include:

- Multi-scale control: Integrating decision-making from the nano (material, product) to the macro (territorial or national strategy) levels, accounting for complex interactions and delayed impacts.
- Flow traceability: Using digital twins to model and monitor material flows throughout their life cycle, providing increased transparency for industrial stakeholders.
- Uncertainty management: Developing robust tools based on artificial intelligence, machine learning, and data fusion to handle heterogeneous, incomplete, and uncertain information.
- Flexibility and adaptability: Leveraging digital platforms and simulation tools to enable rapid adjustments to market, regulatory, or material availability changes.
- Dynamic orchestration: Coordinating data flows and real-time decision-making to optimize the overall performance of value chains.
- Subsystem autonomy and coordination: Ensuring interoperability between actors while maintaining their autonomy through distributed, reconfigurable architectures.
- Hyperspectral analysis and material sorting: Developing advanced material characterization technologies, such as hyperspectral imaging and deep learning, to improve sorting, separation, and regeneration of complex materials.

Research Problem Addressed in this Thesis

The objective of this thesis is **to propose innovative evaluation and optimization criteria, explicitly integrating the three pillars of sustainable development**: environmental, economic, and social. The proposed criteria will be **tailored to the specific characteristics of regeneration value chains.** Particular attention will be paid to the recycling of materials on the one hand, and the recycling of complex products on the other.

The originality lies in the integration of environmental and social impacts not only in the definition of evaluation criteria and indicators but also in optimization objectives. While economic aspects will be considered, the proposed framework will account for multi-scale levels of decision-making and also analyze the impact of digital solutions.

- Environmental aspects will be addressed through Life Cycle Assessment (LCA) methods, as well as with regard to product lifetime extension, second-life opportunities, pollution reduction, and resource consumption induced by recycling processes. The reuse of products, materials, and by-products generated from recycling is a growing environmental concern reinforced by regulations. Developing indicators that capture these specificities represents a major scientific challenge.
- Social impacts will be assessed with regard to employment (e.g., job creation, societal acceptance), changes in work organization, and territorial effects.
- Economic evaluation will reflect the particularities of the recycling sector, focusing on optimizing cost-benefit ratios and assessing the profitability of proposed solutions. Multiple indicators and optimization criteria will be proposed to measure the economic impact of reusing products, materials, and by-products according to their potential end-uses and different reuse scenarios.

These indicators will be tested on simplified and elementary regeneration chains to assess their relevance and impact. Furthermore, they will be evaluated across multiple reuse scenarios to account for potential recovery pathways of regenerated products and materials.

State of the Art

Recycling is a key component of circularity, which has become a prominent theme with numerous ongoing projects and many articles in the literature (Sautereau, 2024).

To effectively address environmental issues, it is essential to link recycling challenges with an increase in product usage (Makowski, 2024) and a reduction in waste (Le Hesran, 2019). One of the significant challenges in the recycling sector is the collection of recyclable products. Additionally, as highlighted by Jäämaa and Kaipia (2022), various specific barriers for each recycling stream need to be addressed.

As Olatayo (2023) points out, it is crucial to define the right metrics for recycling within an appropriate framework. Unfortunately, this area has not been thoroughly explored in the existing literature, making it all the more important to study, particularly since the unique characteristics of different sectors must be considered. Furthermore, metrics related to social impacts have not been much investigated, even though they represent a major concern. It is also important to recognize that economic metrics, which are commonly used in literature, cannot be overlooked. Combining these different metrics (Popien, 2024) presents a significant scientific challenge. Beyond recycling value chains, regeneration value chains offer many research opportunities, and new metrics to measure and improve its effectiveness are needed. The topic of regeneration value chains and its associated opportunities remains largely underexplored in the literature.

While digital tools are increasingly employed for environmental issue, their effective use (Bai et al., 2022) and the sustainability of their impacts warrant further examination. This is an area that remains poorly explored in the literature.

Scientific Challenges

- Identifying indicators that reflect the specific characteristics of regeneration value chains.
- Integrating indicators in a coherent and operational way within a multi-level (micro, meso, macro) framework.
- Managing potential conflicts between the divergent objectives of stakeholders (industry, local authorities, citizens, regulators).
- Measuring the robustness and actual impact of indicators despite variability or fragility of real-world data.
- Developing indicators to assess the systemic impact of digital solutions (digital twins, collaborative platforms). Measuring how digital innovations affect the overall performance of regeneration value chains remains a major scientific hurdle, requiring novel methodologies to capture indirect effects.

Action Plan

To achieve the objectives of this PhD, the following plan will be followed:

- The PhD thesis will begin with a bibliographical study that follows two main axes:
    - An inventory will be conducted of the various existing indicators and optimization criteria related to complex value chains.
    - An analysis of the articles pertaining to the recycling sector will be undertaken to identify the specific characteristics of this sector, ensuring that these are taken into account in the research.
- To thoroughly understand the characteristics of the recycling sector and maintain coherence throughout the project, the PhD student will exchange with other researchers involved in the project and incorporate their findings concerning the structuring of the value chain.
- Proposed indicators for assessing the regeneration value chain, along with criteria for its optimization, will be proposed and evaluated. Given that the study of regeneration value chains is inherently multi-criteria, frameworks for combining various criteria and indicators will be developed and tested.
- To evaluate the impact of the proposed criteria, representative simple cases of different regeneration value chains—considering particularly specificities of the plastic, textile, and battery sectors—will be constructed in collaboration with other project stakeholders.
- Regular collaboration with the work package focused on the design of methods and tools will be essential to ensure project coherence and mutual enhancement. The indicators and optimization criteria will be tailored to align with the proposed methods and tools.
- Lastly, indicators to measure the impact of the proposed digital methods and tools will be developed and assessed in conjunction with other work packages within the project.

References

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Thesis Information

This PhD is part of a joint supervision between G-SCOP (Laboratoire des Sciences pour la conception, l'optimisation et la production de Grenoble, France) and DISP (Décision et Information pour les Systèmes de production, Lyon, France).

Location: G-SCOP, Grenoble, France

Expected Start Date: October 2025

Please note that the confirmation of funding for this project is expected in August or September 2025.

Desired Profile:

Professional skills: autonomy, strong English proficiency, motivation for research in sustainable development, computer science, optimization, industrial engineering.

Application Materials: CV, cover letter, summary of Master's research work, transcripts of records, and any other documents supporting your motivation for this PhD.

Application Deadline: August 22, 2025, 12:00 PM
Notification for Interview: no later than August 29, 2025

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