PhD Thesis Proposal:
System-of-Systems Design and Modelling of a Multi-Level Recycling Value Chain

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 PhD is to design and model the recycling value chain as a true System of Systems (SoS), explicitly addressing the complexity arising from the multiplicity and diversity of stakeholders, their interactions at various levels (local, regional, national), and their potentially divergent goals. The developed architecture will aim to enhance the agility, flexibility, and overall resilience of the network while ensuring its robustness and long-term viability in the face of regulatory, economic, and technological changes.

Coherently with the objective, the following scientific contributions are expected.

The first scientific contribution will focus on designing a multi-level architecture that enables the coherent integration of local initiatives such as industrial symbiosis (micro level) with regional and national recycling strategies (meso and macro levels). The modelling approach will rely on the foundational principles of Systems of Systems engineering, including the explicit definition of actors' capabilities in order to clearly structure their roles, responsibilities, and interactions within the ecosystem.

The second contribution is the formalization of generic and adaptable modelling patterns to represent dynamic interactions between actors, product flows, and regeneration processes. These patterns will facilitate reuse, generalization, and adaptation of the models to different industrial contexts, thereby reducing the time required to design or reconfigure the network.

Moreover, given the fast evolution of technologies, regulatory frameworks, market conditions, and the possible emergence of new recycling actors, a structural adaptability and dynamic reconfiguration mechanisms must be incorporated. These capabilities are essential to ensure the architecture remains responsive and does not become rigid or obsolete. An agent-based modelling approach is then particularly suited to capture such dynamics and can be adopted for implementation and validation.

Particular attention will also be paid to the articulation between the different decision-making levels (strategic, tactical, operational) and the modelling of multi-actor decision processes. This approach will enable a better understanding of the complexity of governance and management mechanisms within recycling value chains, while supporting the precise definition of required data, its update frequency, and its aggregation level.

Scientific Challenges and Objectives:

- Modelling and managing a System of Systems composed of heterogeneous stakeholders with distinct, and sometimes conflicting, objectives.
- Integrating local (e.g., industrial symbiosis), regional (e.g., territorial networks), and national (e.g., sectoral policies) levels into a unified system architecture.
- Formally defining capabilities and leveraging them in a systems engineering perspective to support inter-actor cooperation.
- Establishing a robust methodological framework to identify reusable modelling patterns and determine their applicability across various industrial scenarios.
- Implementing and validating the performance of multi-level, multi-actor architectures using suitable simulation tools, such as multi-agent systems.

Action Plan

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

1. **Literature Review and State of the Art** (Months 1–12)
   - Study of Systems of Systems (SoS) engineering principles.
   - Review and analysis of multi-level architectures in the circular economy, including the role of industrial symbiosis at the local level and its integration into regional and national strategies.
   - Review and analysis of existing modelling patterns and simulation-based approaches in recycling ecosystems.
2. **Definition of the Stakeholders and their Decision-Making Needs** (Months 6–10)
   - Identification and classification of stakeholders involved in recycling value chains.
   - Characterization of their needs, capabilities, objectives, and roles.
3. **Architecture Design and Modelling Pattern Development** (Months 10–18)
   - Design of a reference architecture for the recycling ecosystem as a System of Systems.
   - Formalization of reusable and adaptable modelling patterns for actor interaction, material flows, and recycling processes.

- Structuring of coordination rules and integration of multiple viewpoints and objectives.

4. **Modelling and Simulation** (Months 18–30)
   - Implementation of the proposed architecture using a multi-agent simulation framework.
   - Development of scenarios to assess dynamic coordination and system reconfigurability.
   - Definition and use of performance indicators to evaluate robustness, flexibility, and sustainability.
5. **Case Study and Validation** (Months 30–36)
   - Application of the proposed methods to a realistic case study.
   - Analysis of decision-making effectiveness and adaptability of the architecture in real or simulated industrial settings.
6. **Writing and Dissemination** (Months 6–36)
   - Regular participation in project meetings, workshops, and scientific conferences.
   - Writing of scientific publications in international journals and conferences.
   - Participation in the writing of the concerned project deliverables.

References

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Thesis Information

This PhD is part of a joint supervision between LAMIH and CRAN.
Location: Valenciennes and Nancy (the PhD will take place on both sites; the work schedule and time distribution between locations will be defined at the beginning of the thesis).
Expected Start Date: September/October 2025
Please note that the confirmation of funding for this project is expected in July 2025.

Desired Profile:

Technical skills: Background in systems engineering, modelling and simulation (preferably multi-agent systems), familiarity with Systems of Systems concepts, and interest in circular economy. Experience with tools like AnyLogic or SysML is recommended.

Professional skills: Autonomy, strong English proficiency, motivation for research in sustainable development, and ability to work in interdisciplinary environments.
Application Materials: CV, cover letter, summary of Master's research work, transcripts, 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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