PhD Thesis Proposal
Cognitive digital twin architectures for monitoring, real-time assessment and anticipation of recycling chain dynamics

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 work 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

This thesis aims to develop cognitive digital twin (DT) architectures, to support the monitoring, real-time assessment and anticipation of recycling chain dynamics. It includes to:

- Simulate and anticipate transformations at the meso (inter-organizational networks) and micro (process or actor-specific) levels within recycling value chains.

- Evaluate the economic, environmental and social impacts of variations in decisions.
- Generate real-time insights to inform decision-making and policy development.

The expected scientific contributions are:

- The development of advanced simulation services for the flow of recycled products and materials, enabling "what-if" scenario analysis and decision impact forecasting (thus providing predictive insights to support agile and informed value chain management).
- The System-of-Systems (SoS) integration of the DTs with the existing collaborative information system (IS) to enable physical and virtual components alignment (by exploring the integration of multiple local DTs into a coherent SoS architecture capable of decentralized, asynchronous decision-making).
- The formalization of data flow strategies between physical entities and digital surrogates based on internal and external key performance indicators (KPIs), to enhance system resilience and responsiveness while managing computational load (by generating and adapting DT models from heterogeneous and uncertain data, as well as assessing through sensitivity analyses how data quality impacts forecasting reliability under resource constraints).

State of the Art

Several studies offer foundational insights into how DTs support circular economy transitions and the so-called R-strategies (Mügge et al. 2024), (Ke et al. 2023), (Ciano et al. 2025). While some contributions focus on specific lifecycle stages, others attempt broader integration while recognizing the absence of full lifecycle integration in current DT applications (Han et al. 2023), (Seegrün et al. 2023). Moreover, a particularly important gap concerns the lack of cognition features. Indeed, for DTs to support recycling chains objectives, they must be designed not only as digital tools but also as enablers of collaborative decision processes, supporting alignment between actors, responsibilities, and lifecycle phases. Cognitive DTs extend the capabilities of DTs by integrating reasoning features through artificial intelligence techniques. Despite the lack of literature due to the field's infancy, cognitive DTs are becoming key tools for making systems more autonomous and adaptable (Shahzad et al. 2025). Due to their high level of autonomy, the integration of many such tools in a decision-making support ecosystem calls for a SoS approach (Traoré & Ducq 2022).

Scientific Challenges

- Model discovery and adaptability: building/adapting DT models dynamically from IS data, with minimal latency, to reflect current operating conditions and disruptions.
- Sensitivity and confidence analysis: evaluating how data quality and model configurations affect forecasting reliability, under resource-constrained environments (such as limited computing power or real-time requirements).
- SoS integration: composing local DTs maintained in a distributed recycling ecosystem into a consistent system-wide DT architecture able to support decentralized decision-making, asynchronous updates, and heterogeneous performance objectives.

Action Plan

- Systematic literature review on DT in recycling chains, Cognitive DTs, and SoS of DTs
- Simulation modelling of the flow of recycled products and materials, integrating well-defined KPIs.
- Formalization of data flow strategies between physical entities and digital surrogates, dealing with the decentralized nature of data sources.

- Data assimilation from data sources and the IS supporting the recycling chains to enrich models developed.
- Composition of resulting DTs into a SoS of DTs, capable of supporting decentralized, asynchronous decision-making for recycling chains resilience and responsiveness.
- Computational load balancing in the SoS of DTs.
- Sensitivity analyses to assess how data quality impacts forecasting reliability under resource constraints.

References

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Thesis Information

This PhD is part of a joint supervision between IMS (UMR 5218) and DISP.
Location: Bordeaux (main location) – Lyon
Expected Start Date: Autumn 2025

Desired Profile:

Professional skills: autonomy, strong English proficiency, motivation for research in sustainable development.
Application Materials: CV, cover letter, summary of Master's research work, transcripts, and any other documents supporting your motivation for this PhD.

Application Deadline: September 23, 2025, 12:00 PM
Notification for Interview: September 30, 2025

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