Human-Centric AI and Cognitive Digital Twin Modelling with Semantic Clusters for Intelligent Enterprise Systems

The logistics sector faces increasing complexity in managing diverse data streams and aligning them for decision-making, operational efficiency, and adaptability to market demands. The introduction of Cognitive Digital Twins (CDTs), which combine physical-digital integration with cognitive capabilities, represents a promising solution to these challenges. However, this approach requires overcoming significant hurdles. Semantic heterogeneity, which arises from inconsistent terminologies, data structures, and interpretations across different systems such as ERP, WMS, and CRM, is a critical issue. Additionally, dynamic decision-making necessitates the integration of human expertise into AI-driven systems to effectively adapt to evolving market conditions and unpredictable human factors. Ensuring interoperability and consistency across semantic representations through ontology alignment is another essential challenge in optimizing storage and logistics operations.

This PhD research will focus on creating a Cognitive Digital Twin framework that leverages Formal Concept Analysis (FCA) to identify, structure, and align semantic clusters across logistics datasets. These semantic clusters will be aligned with an ontology tailored to the logistics domain, ensuring consistency and semantic interoperability. Human involvement will be integrated into the AI loop through Human-AI interaction frameworks, enabling collaborative decision-making and reducing the risks associated with human error.

Objectives:

The central objective of this research is to develop a Cognitive Digital Twin framework for logistics that integrates FCA, ontology alignment, and human-AI collaboration. This framework will bridge the gap between physical operations and digital models, enriched by cognitive capabilities. The research will investigate the application of FCA to dynamically extract and formalize semantic clusters from heterogeneous data sources. These clusters will be aligned with a logistics-specific ontology to ensure consistent semantic representation and interoperability.

A key focus will also be the integration of human expertise into AI-driven processes. By designing mechanisms for Human-AI interaction, the research will ensure that machine insights are complemented by human intuition and contextual knowledge. This will involve creating intuitive interfaces and workflows that enhance transparency and trust in AI-driven decision-making.

Through this approach, the research aims to provide a scalable and adaptable solution for logistics operations, addressing semantic heterogeneity and enabling efficient real-time decision-making. The final framework will be validated through prototyping and applied to real-world scenarios at MG-IB, demonstrating its practical impact on storage management and logistics optimization.

Methodology:

The development of Cognitive Digital Twins builds on advancements in several key areas. Digital Twin technology has evolved to include cognitive capabilities, enabling predictive analytics and real-time decision-making in industrial environments. Formal Concept Analysis is a well-established methodology for extracting hierarchical structures and relationships from

data, making it particularly useful for semantic formalization and cluster identification. Ontology engineering has become a cornerstone for semantic consistency, leveraging standards such as OWL and RDF to represent and reason over domain knowledge. Human-AI collaboration, supported by explainable AI (XAI) techniques, has gained prominence as an essential factor in integrating human expertise with AI systems.

This research will adopt a systematic methodology to design and implement the Cognitive Digital Twin framework. The process will begin with data collection and modeling, focusing on identifying sources of semantic heterogeneity within MG-IB's logistics systems. FCA algorithms will be applied to extract semantic clusters from these datasets, which will then be aligned with a logistics-specific ontology developed or adapted for this purpose. Human-AI interaction mechanisms will be designed to enable effective collaboration between machine-driven insights and human expertise, incorporating XAI principles for enhanced transparency and user trust. A prototype system will be developed to integrate these components, validated through application to MG-IB's logistics operations.

The proposed research will significantly contribute to MG-IB's strategic objectives by providing a robust framework for optimizing logistics operations. The Cognitive Digital Twin framework will enhance data-driven decision-making and operational efficiency, enabling the company to address challenges related to semantic heterogeneity and dynamic market conditions. By integrating human expertise into AI-driven processes, the research will foster trust and adaptability, ensuring that MG-IB remains a leader in applying cutting-edge AI technologies to industrial challenges. The validated prototype will not only demonstrate the practical impact of the research but also serve as a foundation for future innovations in the field.

Working Conditions

Contract Time: Three years.

Employer: Université de Lorraine and MG-IB enterprise.

Salary: Between 1800 and 2000 euros net per month.

Expected Profile:

The ideal candidate should have a Master's degree (or equivalent) in computer science, data science, or a related field. Strong analytical skills and a solid background in Artificial Intelligence, data integration, and semantic technologies are essential. Experience with ontology engineering, formal concept analysis (FCA), and machine learning frameworks will be highly valued.

Candidates should demonstrate:

- Mastery of the English language is mandatory; French would be highly appreciated.
- Proficiency in programming languages such as Python or Java.
- Familiarity with enterprise systems (ERP, MES, CRM).
- Knowledge of semantic web technologies and data modeling tools.

- Excellent communication and teamwork skills, as the project involves close collaboration with the MG-IB R&D department and the CRAN laboratory at Université de Lorraine.

The successful applicant will split their time between MG-IB's Research and Development Department in Épinal and the CRAN laboratory in Nancy, France. Regular visits to MG-IB clients in the Vosges region are expected, ensuring alignment between theoretical research and practical applications.

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